CARBON DIOXIDE AND CLIMATE: THE GREENHOUSE EFFECT

HEARING

BEFORE THE

SUBCOMMITTEE ON NATURAL RESOURCES,
AGRICULTURE RESEARCH AND ENVIRONMENT

AND THE

SUBCOMMITTEE ON
INVESTIGATIONS AND OVERSIGHT

OF THE

COMMITTEE ON
SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

NINETY-SEVENTH CONGRESS

SECOND SESSION

MARCH 25, 1982

[No. 115]

Printed for the use of the
Committee on Science and Technology

U.S. GOVERNMENT PRINTING OFFICE
98-227 O WASHINGTON : 1982

H701-85

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CARBON DIOXIDE AND CLIMATE: THE GREENHOUSE EFFECT

THURSDAY, MARCH 25, 1982

House of Representatives, Committee on Science and Technology, Subcommittee on Natural Resources, Agriculture Research and Environment; and Subcommittee on Investigations and Oversight,
Washington, D.C.

The subcommittees met, pursuant to notice, at 9:10 a.m., in room 2253, Rayburn House Office Building, Hon. James H. Scheuer (chairman of the Subcommittee on Natural Resources, Agriculture Research and Environment) presiding.

Present: Representatives Scheuer, Gore, Shamansky, Volkmer, Carney, Walker, and Sensenbrenner.

Staff present: Dr. James C. Greene, science consultant; Maryanne C. Bach, technical consultant; Mr. David Clement, minority counsel.

[The opening prepared statement of Mr. Scheuer follows:]

Opening Statement of Hon. James H. Scheuer

This joint hearing of the Subcommittee on Natural Resources, Agriculture Research and Environment and the Subcommittee on Investigations and Oversight will come to order.

In recent decades man has become capable of causing catastrophic and, in many cases, irredeemable harm to the planet.

If today's worst case scenario becomes tomorrow's reality, it will be too late to reverse the atmospheric carbon dioxide buildup or to ameliorate the adverse human and environmental impact.

However, if we have a sufficient research program that will provide the necessary answers, then future generations need not pay for our environmental pollution.

While I support elimination of all unnecessary expenditures by the Federal Government, many areas of the budget are receiving severe and needless cuts.

Environmental research is one area that if cuts are too severe, the temporary savings will be offset by tremendous cost to future generations who will have to restore the damaged environment.

In a February Gallup poll the question was asked, "Do you think Federal spending in the following areas should be cut further, increased or remain the same?"

In the area of "Protecting the environment" only nine percent indicated it should be cut further, but forty-four percent said it should be increased.

An additional thirty-seven percent thought that federal spending should remain the same.

This survey was based on the fiscal year 1982 budget.

This is one of the latest of several polls taken over the past year which indicate that protecting the environment is a high priority issue even in these times of a troubled economy.

Clearly, carbon dioxide research falls into the classification of protecting the environment.

The dimensions and nature of the carbon dioxide buildup and the resulting greenhouse effect are, as yet, not fully understood.

However, the potential impact on the environment is staggering.

It has been theorized that global warming could result in significant changes in weather and climate patterns around the world.

Effects which have been projected for the United States include a warmer and drier climate in the grain producing areas of the Midwest, with a consequent decrease in productivity.

Some studies have projected a loss of arable land as a direct impact of climate change, and a threat of flooding and perhaps even loss of some coastal areas due to warming of polar regions and thinning of polar ice caps.

Today's hearing will examine recent research results that provide some of the first measurable evidence of the impact of increasing levels of atmospheric carbon dioxide on the environment.

We will also explore what research is needed in the future.

In this hearing we will also hear testimony from officials from the Department of Energy.

They will address the President's budget request for the carbon dioxide program for 1983 and the changes in the program's scope and direction.

Mr. SCHEUER. This morning the joint hearing between the Oversight and Investigations Subcommittee of the Science and Technology Committee, chaired by the distinguished member from Tennessee, Al Gore, and the Subcommittee on Natural Resources, Agriculture Research and Environment will address the extraordinarily important and very perplexing subject of the carbon dioxide effect, or "greenhouse" effect. The hearing will come to order.

I would like to call on my distinguished cochairman, Mr. Gore of Tennessee, for his opening remarks.

Mr. GORE. Thank you very much, Mr. Chairman, and good morning to all.

Today these two subcommittees are in a somewhat unique position because, while many of the matters that come before congressional committees are fairly dry and prosaic, today we are examining a global issue that evidently has the potential to greatly disrupt the world's environment as we know it.

Since the early 1950's, scientists have become aware that the concentration of carbon dioxide in the atmosphere has been increasing. These increased levels have given rise to the phenomenon that I am sure everyone is familiar with, the "greenhouse effect."

The debate over the greenhouse effect has undergone a very important transition over the past decade. Ten years ago, it was viewed as the pet theory of a few scientists, perhaps on the fringes of science, but it has slowly and inexorably moved into the mainstream of scientific thought. There is now a broad consensus in the scientific community that the greenhouse effect is a reality.

Perhaps the best illustration of this is that we now have scientists of international stature, such as Melvin Calvin, our first witness, acknowledging the existence of increased carbon dioxide levels in the atmosphere, and the resulting environmental impacts. As a recent editorial in the Washington Post explained, it is not just the "sandals and granola" crowd who support the need for accelerated research into the problems associated with the greenhouse effect.

These two subcommittees held a hearing on the greenhouse effect last July. Since that time, there have been important advances in research. While last summer we primarily debated the levels of carbon dioxide, since that time, Dr. Hansen and Dr. Kukla have gone a step further. They have correlated the increased levels of carbon dioxide with the shrinking of the Antarctic ice cap and an increase in worldwide sea levels.

So it is apparent that we are no longer dealing with merely a provocative theory. We are hearing this morning from witnesses who are presenting not just theory but hard facts and evidence. The greenhouse effect is apparently a real phenomenon, even though areas of uncertainty remain. It would appear, therefore, painfully obvious that we should continue to develop more specific and reliable information about the causes of this phenomenon, about its long-term impacts, and about what efforts we could undertaken to mitigate the potentially severe human and environmental consequences.

These committees are, therefore, amazed that the administration has decided to substantially cut the Department of Energy's budget for research in this area. They are cutting the carbon dioxide budget drastically in the face of this startling new data and in spite of their own Research Advisory Board's conclusion that research into carbon dioxide be given top priority and more funding, and in spite of commitments made to these two subcommittees last July.

We look forward to examining this important phenomenon. We wish to thank all the witnesses in advance for taking the time to appear here today.

Mr. SCHEUER. Thank you, my colleague.

Now for the distinguished ranking minority member of this committee, Congressman Bill Carney of New York.

Mr. CARNEY. Thank you, Mr. Chairman.

The importance of this hearing I see as twofold. This is a critical time when the state of scientific research is producing more and more evidence that mankind is increasing the carbon dioxide content through activities such as burning of fossil fuels and deforestation. Also, the United States is experiencing the painful return to economic recovery.

The combination of these two factors has necessitated the scrutinized review of our Federal programs and future investments. As are the problems with acid rain and toxic wastes and the pollution of our streams and lakes and rivers and oceans, the impact of higher carbon dioxide levels in the atmosphere represents a problem of global proportions.

We cannot overlook the relationship between decisions we make now in the atmospheric situation and what will happen one or two or three or maybe even four decades from now. Such is the dilemma of all of our environmental concerns. We are constantly looking to science for the guidelines upon which we base our legislative action. Yet the time restraints under which science and the Congress work do not always complement one another.

For science to work efficiently, hypotheses must be tested and retested before a theory is formed. The progression from theories to facts requires additional time and research.

That the carbon dioxide levels are increasing in the atmosphere is a scientific fact, Mr. Chairman. That it is closely related to global energy problems is also something that we are very well aware of. The quantitative estimates of costs and benefits are not yet possible to obtain, but the range of possible outcomes of the problem can be estimated.

Our reason for holding these hearings today is to determine the emphasis and direction of the involvement of the Department of Energy's program on carbon dioxide. I commend you, Mr. Scheuer, for your choice of this topic, which is of growing concern, and I am looking forward to hearing from our most distinguished witnesses, and I yield back the balance of my time.

Mr. SCHEUER. Congressman Shamansky?

Mr. SHAMANSKY. Thank you, Mr. Chairman.

Frankly, I have always responded to the word "greenhouse" as something that was basically benign. I have always enjoyed going inside of greenhouses, and everything seems to flourish in there. I think the description of this as the greenhouse effect is a little confusing to the layman. I am beginning to feel like something inside a microwave oven, which might be a more exact description of the effect on those of us inside. So therefore I suggest, for the sake of argument, that we refer to this as the "microwave oven" effect because we are not flourishing too well under this; apparently, we are getting cooked, and maybe we ought to convey a little more accurately what we are facing unwittingly.

Thank you, Mr. Chairman.

Mr. SCHEUER. Thank you, my colleague.

Bob Walker of the State of Pennsylvania?

Mr. WALKER. Thank you, Mr. Chairman.

Mr. Chairman, today I have a sense of deja vu as we hear testimony on the well-known greenhouse effect. I have been a member of this committee now for more than 5 years, and for 4 of those years I served as the ranking minority member on the subcommittee which you now chair. In each of those 5 years, we have been told and told and told that there is a problem with the increasing carbon dioxide in the atmosphere.

We all accept that fact, and we realize that the potential consequences are certainly major in their impact on mankind. But I cannot help but wonder how much research is required to identify a problem. How frequently must we confirm the evidence before we commence taking remedial steps? And, finally, once a problem is identified and correction actions are underway, what additional research, if any, is necessary, or can we shift to a monitoring mode and keep track of the severity of the problems and the success of our corrective efforts.

Mr. Chairman, I will listen to the evidence presented today and make my own evaluation as to what research level is supportable, but I cannot help but say that it appears that much of the basic research has already been accomplished. The results have been validated and they have been revalidated. Perhaps I am being somewhat cynical, but I think that Congress has a duty to the taxpayers of America to be somewhat cynical.

In the years I have been associated with this committee, I have been impressed with the fact that the result of virtually every federally funded research project is that more research is needed, and if we question the Government witnesses about the need for more research, they point to the academic community, who are usually quick to support the need for additional research.

But that streak of cynicism reminds me that the Federal researchers count on us for their budget and that most of the research done in the academic world is largely dependent upon Federal funds.

Unlike the commercial industrial laboratory, there is no bottom line to tell us in absolute terms of profit and loss how much research is enough or how much is too much. Because of that, we unfortunately have a tendency to reinvent the wheel, and while each new model has some new feature or new frill to it, it is always the same old wheel.

In a time of tight budgets when competition for research resources is fierce, we should be encouraging those projects which have already been sufficiently researched to move forward into the development or resolution stage. At the same time, we should be alert to the breakthroughs or new discoveries which merit additional research to further expand the frontier of man's knowledge.

Our job here today, it seems to me, is to see which alternative applies. Thank you, Mr. Chairman.

Mr. GORE. Will the gentleman yield on that?

Mr. SCHEUER. Of course.

Mr. GORE. I know this is not the time to have an interchange on this. I respect my colleague's statement, and he may be quite right.

However, the actions that would be required by this country and other countries to mitigate the consequences of the greenhouse effect should we decide that it really is happening are so massive, so sweeping, that they would challenge the political will of our civilization.

As a consequence, it seems to me that the degree of certainty required before contemplating actions of that magnitude is greater than would be the degree of certainty otherwise.

So, while I respect my colleague's conclusions in his statement, it does seem to me that if we can elevate the degree of certainty, we will have a better chance of summoning up the political will to address this problem in a fashion that it may well have to be addressed.

I thank my colleague for yielding.

Mr. WALKER. If the gentleman would yield, I certainly agree with him on that point. My point is simply this, that the testimony is rather clear that we have heard. In the 5 years that I have been around the committee, the testimony has always been clear. As a matter of fact, I see charts here in the room, and so on. They are charts that I have seen other times which tell us the same things, the point being that I think it is very important that this committee be in the forefront of providing the kind of research that tells us that we have got a problem that has to be addressed.

But to continue to tell us that problem over and over again and then not reach out to try to summon up the political will which may be necessary to resolve those problems does not really make much progress. That is basically my point. I am not so certain how many times we have got to go through the same motions before we have to move to the next stage of saying to people, now is the time; the research is clear; it is up to us now to summon the political will to which the gentleman refers.

Mr. SCHEUER. Let me add a further footnote to your comments, Congressman Walker.

You were the ranking minority member of the Subcommittee on Government Research that I chaired 4 years ago, and you were a thoroughly hardworking and constructive and supportive member, and you continue to be. I wish there were more like you around the Congress.

I have not noticed very many members of your party saying we should stop pouring so much money into research on acid rain because the facts are in; now let's get on with remedial programs; we know enough to know that urgent remedial steps are required.

Mr. **Walker**. Will the gentleman yield on that point?

Mr. **Scheuer**. No; let me finish.

Mr. **Walker**. Well, I would just say that on that I am not certain all the research is in on acid rain.

I would be very favorable toward moving forward with research in that area because I think that there is a lot more research that probably needs to be done in that area to give us some assurances of the direction in which we have to head.

So I thank the gentleman for yielding.

Mr. **Scheuer**. I notice that the Surgeon General of the United States tells us that tobacco, cigarette smoking, is the greatest single threat to the health of the American people extant today, and that 300,000 people a year die of cancer and other tobacco-related causes and that the total cost to our society of the deaths and the unemployment and the direct and indirect costs that flow from tobacco total somewhere around $40 billion or $50 billion a year.

Yet the spokesmen for the tobacco industry and many Members of Congress say that the cause-and-effect relationship still has not been established and that more research is needed. Even within days of the time the Surgeon General made his report and recommended stronger statements on the cigarette cartons, the administration apparently backed away fast and did a soft step and slow shoe and backpedaling act up here and pulled away from those recommendations.

Already, we see significant interests at work weakening the Clean Air Act, although there is considerable evidence that the pollutants that we spew into the air from our industrial enterprises, from our utilities and are causing severe health and environment effects.

I admit the data are not perfect on the Clean Air Act. I admit the data are not perfect on acid rain, and perhaps there is not a mathematical certitude even on the health effects of cigarette smoking. But surely there should be enough evidence there to encourage thoughtful men like yourselves to go ahead.

But, unfortunately, the reality that we have to face is that the evidence has to be overwhelming. I think, in the case of carbon dioxide, the greenhouse effect, even the scientists say, and presumably we are here to hear this morning, not of the need for taking remedial measures based on the data that we now have in hand and well under control, but I think they may well tell us that there is more that we ought to know.

Given the condition that a 3- to 7-degree increase in the Earth's temperature will occur in 100 years and damage by subtle effects and the predicted horrendous, catastrophic effects around the world will take place, then attempting to present this costly damage seems well worth the paltry sum of $17 million that we requested of the administration. They have cut us down to $4 million, approximately the cost of two M-1 tanks that don't work very well, approximately one-quarter of 1 day's military budget.

With the hundreds of billions that we are going to have to spend addressing ourselves to this problem and the related problems of clean air and acid rain, and so forth; with the enormous international collective action that has to take place because not all of the causes of the greenhouse effect come from the United States—they come from all of the developed world, across the whole belt of Europe, including Russia and the satellite countries. When you think of the extraordinary effort that will have to be made on a transboundary approach to the problem, it seems to me that to begrudge $10 million, $15 million, or $20 million in research to hammer down as many of the doubts and question marks as possible ought to be well worth it.

None of my colleagues, in their very thoughtful remarks, mentioned the specific problems that we are going to be facing here and around the world if we don't get a handle on the greenhouse effect.

In our own country, extraordinary climatic changes will be caused by this 3- to 7- or 8-degree increase in temperature over the next generation or two. The Midwest, the grain-producing area of our country that feeds a good part of the world, will become warmer, hotter, and drier, and less productive.

Much of our coastal areas may be flooded if rising temperatures in the Arctic melt the Arctic ice cap.

All of these threatening events are speculations. We cannot document them at the present time with mathematical certitude, but they seem to be there. The temperature does seem to be rising.

In our own country, vast areas will have to be abandoned, due to coastal areas that are flooded. We are told that 40 percent of the State of Florida will have to be relocated from its coastal areas.

Mr. GORE. It could happen.

Mr. SCHEUER. Let me footnote for the benefit of all of my colleagues, all of this is speculative; none of this is determined with mathematical certitude. They are threats, they are dangers that we must address ourselves to.

We are told that the water flow of the Colorado River could be cut in half.

Around the world, the prospects are even more devastating. Regions of the world that are already dry, hot, and arid—India, China, Bangladesh, and the entire sub-Saharan belt of Africa—will become even more desiccated if the global climate change predicted from the CO_2/greenhouse effect occurs. These areas will become less capable of sustaining human and animal life, and agriculture.

When one thinks of the terrible social pressures that rend societies apart, at their present state, the inability to provide the basic human needs of their people, one can only be appalled at the threat of further retrogression, further deterioration in the ability of those countries, pitifully poor as they are now, and even lessened ability to sustain life, provide adequate food and sustenance to their people.

The internal threat to stability of government, the threat that this would provide to peace and security and amity among nations, the threat of violent confrontation over the dwindling resources of arable land are almost too appalling to contemplate. We pay a dreadful price by inaction.

I can only say to my distinguished colleague from Pennsylvania, who has been a thoroughly useful and constructive member of the Science and Technology Committee, that if the price we have to pay to be sure of collective action in this country and the cost of getting some kind of effective collective action internationally to reduce these forces that are global in nature, these Earth-circling temperature changes that will have inexorable global effects, if the cost of that is spending another $25 million or another $50 million in research then this is money well spent when compared to the money that might have been saved through proposed budget cuts.

I think that this extra, absolutely minor sum, in comparison to the devastation that may occur from inaction is very worthwhile insurance, indeed.

So, as we call the witnesses, we will be asking some hard questions about the administration's budget decisions on their reduced requests for funding. Before we do, Mr. Volkmer from Missouri is here, and I would like to ask him for any opening remarks.

Mr. **Volkmer**. I have no opening statement.

Mr. **Scheuer**. All right. Then let us call, without any further ado, Dr. Melvin Calvin, professor of chemistry at the University of California at Berkeley.

We are very happy to have you, Dr. Calvin. You have some highly thoughtful and concerned Members of Congress here from both parties, and we are eager to hear your words of wisdom. Tell us what the threat is, as you perceive it; how serious is it; how avoidable is it; what do we need to know to take the thoughtful, cost-effective, sensible actions that are justified by the data base; and, in effect, tell us what you would do if you were sitting up here making these very tough value judgments that the voters have asked us to make for them.

Mr. **Gore**. Mr. Chairman, may I also welcome Dr. Calvin and note for our guests that Dr. Calvin was awarded the Nobel Prize in 1961 for studies that included the carbon cycle and carbon dioxide in addition to photosynthesis, and we are most pleased to have you here.

Dr. **Calvin**. Thank you, gentlemen.

Mr. **Scheuer**. May I say before you start, Dr. Calvin, that your prepared testimony will be printed in full at the conclusion of your oral presentation, so please take whatever time you need and address us informally.

STATEMENT OF DR. MELVIN CALVIN, PROFESSOR OF CHEMISTRY, LAWRENCE BERKELEY LABORATORY, UNIVERSITY OF CALIFORNIA AT BERKELEY

Dr. **Calvin**. Thank you very much.

I welcome this opportunity to address this committee in the hope that some of my sense of urgency can be transmitted to you.

You should realize, when I heard Congressman Walker say that he had been on this committee 5 years and had heard much of the data over and over again, I sympathized with him. I have been looking at it for a considerable length of time.

The thing that can be added this year to the curve that you have there—incidentally, I have passed out a print of that which has 2 more years on it, so that the accelerating rate of rise of the carbon dioxide is a little more visible than it is on that date. The mechanism by which this increasing blanket of carbon dioxide around the surface of the Earth produces the consequence that it does is also shown in another picture which I have distributed to you simply for the sake of emphasizing how the system works.

The picture here shows the orange-colored blanket of carbon dioxide transparent to the visible light of the Sun, which is represented by the yellow arrow, but opaque to the infrared light into which all of that visible light energy is converted when it strikes any part of the surface of the Earth.

This is the problem. The carbon dioxide, as you know, is not transparent to that infrared light, and it cannot escape and is reflected back to the surface of the Earth. That is essentially the mechanism of the process, and I am sure you have heard it many times.

Mr. GORE. We tried to illustrate that in——

Dr. CALVIN. That right there, yes. It is the same thing. This is a little more graphic, and I thought perhaps you would like to see it.

Now, what additional confirmatory evidence do we have that something is happening? This is a physical result, that rise in carbon dioxide, and there is no ambiguity about it. Most of it is the combustion of fossil carbon, and I can tell you how that was determined if you wish.

The physical consequences of that rise are also unambiguous, given no other countervailing effects. The carbon dioxide has the properties I just described to you, and this is what is going to happen, what is happening.

The question, then, is are there any early warning signals? I say early warning signals because we cannot wait until the signals are so big that they are out of the noise. It is much too late then. You cannot do a thing about it when the signals are so big that they come out of the noise. So you have to look for early warning signals, minute signals, that will give you a clue that this is happening; it is on its way.

People have been looking for those signals now all over the world, and you will hear from three, at least, I have been told, of the primary researchers who are gathering or searching for those signals. One of them is a group at NASA who has found a temperature rise that corresponds to the expected temperature rise from such a change in the carbon dioxide level.

But the two that have added to it in this past year which I suspect Mr. Walker and the others have not seen is the fact that the south polar ice cap has already begun to melt, and this was reported this year.

Now, in consequence of the melting of the south polar ice cap—this was done, by the way, by our satellites compared to the atlases produced by the U.S. Navy and the Russian Navy in the Antarctica of some years back, and I think that monitoring must continue with more precision so that a few tenths of a percent change per year could be detected with certainty so we will know what is happening—which is another new piece of information which has just been made available to us in this past year is that if that south polar ice cap, which is now sitting on the top of the Antarctica rocks, is melting, where is the water going? It is going into the ocean.

Is there any way to determine that that is happening? The answer is yes, and there has been published in "Science" in the last 6 months a measure of the change in sea level over the period from 1890 to 1980, and the change in rate at which that sea level is rising is quite obvious. Now again, this data will be presented by the authors, whom I understand are here, and I will not embellish it any further; simply to point out that the early warning signs are becoming more and more unambiguous, which is what people are asking for.

Now, what are the consequences? Well, there is one other consequence of this, of moving the water from the south polar ice cap to the oceans, and this is an interesting one. If ever any of you have seen a figure skater on the ice, you will remember that when the figure skater gets going, spinning, he keeps his arms in. Now, as he moves his arms out, he spins slower and slower, and the reason he spins slower is that the momentum, the angular momentum of his body, becomes bigger, because the mass of his body is now spread out further.

That is exactly what is happening to the Earth. The water, which was originally on the pole, on the spinning axis, is gradually moving out to the outside, and the angular momentum of the Earth is getting greater, and it is slowing down. That is another interesting fact which I did not know until just a week or two ago. That corresponds to this same quantitative consequence.

Well, now, the gathering of such early warning signals must continue, as I agreed, in order to assure us that we are heading in this direction with the confidence we need to deal with the problem because it is a problem of global concern, as the chairman has reported.

In fact, in the many appearances I have made on this subject, one of the factors which I try to emphasize each time is the impending—how shall I say it?—the impending human struggle, a true Darwinian struggle for resources, which this sort of thing is going to induce. The detailed form in which that struggle will take place is something I cannot predict because a war will break out here or there or elsewhere, and I am sure all of you are familiar with how these things happen, and that is what I think Mr. Scheuer was referring to, and I agree with him entirely that that kind of a catastrophe is part of the offing.

The drowning of southern Florida is something that people have heard about. The drowning of the whole coastline from New Jersey into the gulf, is also part of this thing. I don't know what will happen to Tokyo. I think it will have some problems, too. It is a global problem.

Now, I am convinced that most of the problem lies in the combustion of carbon that has been in the Earth for several hundred million years, and we are burning it at a rate millions of times greater than it was laid down. It is the burning of carbon that produces this result. The burning of coal produces it twice as fast as the burning of oil. I would suggest to Mr. Walker that if he could persuade his coal companies in Pennsylvania to do the research necessary to keep the carbon dioxide out of the atmosphere, he would be doing a great service not only to the country but to the world.

That is not going to be cheap. It is going to be very expensive to do that.

Mr. SCHEUER. To do the research or to do the actual applied technology?

Dr. CALVIN. The applied technology. There is research involved in this because the detailed way in which you are going to filter the carbon dioxide out of the stacks at powerplants has not been determined. It is bad enough to try to filter the acid out of the powerplants, which is only a few tiny percent of the gas that goes up the stack, but the carbon dioxide represents the body of the gas that goes up the stack. It is going to be a real task to do that, a very expensive task, and it is something that the producers of that carbon dioxide should be conscious of and beginning to—not beginning; they should have been doing—make some effort to reduce that emission. I do not see how they can do it with the costs that it is going to entail, but maybe, with development, those costs can be reduced.

Now, the best way, of course, to avoid that problem is not to put the carbon dioxide up there in the first place. Now, there is no way to get energy from fossil carbon that has been in the ground 100 million years or more without producing carbon dioxide, no way, no matter how you do it, whether you burn the coal directly in the furnace, in the boilers and make steam, or whether you convert it first into oil or whether you convert it first into gas. There is no way to get the energy out of the coal or out of the oil, for that matter, without producing carbon dioxide. The mechanism of producing energy is the mechanism of combining oxygen with carbon. That is what you have to do, and you cannot get it any other way.

So that is one possibility: avoid doing that. The only way I know of avoiding doing that and having liquid fuel, which is the most important portable energy source we have—our present transportation system is totally dependent upon that highly concentrated chemical liquid fuel which we call hydrocarbons. We get it from petroleum, you can make it out of coal if you want; but, better yet, both the coal the oil were made 300 million years ago, or thereabouts by the green plants collecting the Sun, taking the carbon dioxide out of the atmosphere, and making reduced carbon out of it, including oil and gas and coal.

What we are doing now is burning that stuff that was put down there 300 million years ago, at a rate millions of times faster than it was put down.

If we could do it on an annual basis, each year, to take what the plants have taken out of the air, made into reduced carbon, make oil out of it and then use it as carbon or as oil, we would have no net new carbon dioxide per year, no net gain. But we would have the energy we want by converting, essentially, the Sun's rays into liquid fuel.

There are a number of scenarios which indicate what we could expect to happen if we don't do anything. I don't know if you want to hear that, Mr. Chairman.

Mr. **Scheuer**. Yes; we do.

Dr. **Calvin**. I have here—I don't know whether they have been distributed—some charts which show what will happen over the next 50 or 60 years on carbon dioxide emissions, carbon dioxide concentration, and the average temperature change, if we go on with a 50-terawatt fossil fuel strategy, the carbon dioxide emissions and the temperature changes are very large indeed. They go up to 4 or 5 degrees. A 4- or 5-degree rise in the global temperature means an enormous change in the agricultural pattern of the Earth, and if that happens within two generations of the human race, I do not think the human race can adjust to it that fast; it is bad enough to adjust to it in several hundred years, to that big a change in agricultural patterns over the surface of the Earth. To do it in one or two generations, I think, is asking too much of mankind.

Mr. **Scheuer**. What is the likely timetable?

Dr. **Calvin**. It says here about 50 years, if we continue to burn fossil carbon.

Mr. **Scheuer**. That is about two generations.

Dr. **Calvin**. That is about two generations, you see. That is the trouble. So we don't have too much time. I think we have to find alternative strategies now, get them into operation so as to reduce that carbon dioxide threat.

There are a number of other things that could be said about this, but I would defer to any questions that you might have to raise.

Mr. **Scheuer**. Well, thank you very much, Professor Calvin.

Congressman Gore?

Mr. **Gore**. Thank you very much, Mr. Chairman, and thank you, Dr. Calvin, for——

Dr. **Calvin**. Can I go, or do you want me to stay?

Mr. **Gore**. No, no; we want you to stay. I was thanking you for your statement. I will thank you for your whole appearance later on. We have got a lot of questions for you.

You know, a lot of people look at this problem and have a hard time really believing that it is real because it conflicts with the normal definition of commonsense. The world changes very slowly. We find it difficult to believe that these kinds of dramatic changes which have occurred in the past during geologic time can actually occur during the lifetime of people alive today.

But the reason why scientists of eminent credentials like you are telling the country that this is something we really ought to worry about is that global civilization has now reached the point where it is capable of producing worldwide changes of a magnitude unthinkable in the past.

Specifically, the Industrial Revolution, which began over 100 years ago, led to the dramatic increase in the emission of carbon dioxide into the atmosphere. As the chart prepared by the Department of Energy indicates, it began to increase in the last century, and then after World War II, the amount of carbon dioxide emissions into the atmosphere just really shot up dramatically.

These are actual measurements of that taking place. For those who are not familiar with these charts, that is a summer/winter cycle, and each cycle is defined by about a dozen measurements in the atmosphere. The peak is the winter peak, when the vegetation in the Northern Hemisphere, where the bulk of the land mass is, is not absorbing carbon dioxide. The lower peak is the summer peak, when the plants are absorbing a lot of carbon dioxide, and it is lower in the summer.

As you can see, it goes steadily upward year by year. As you noted, 3 years have now been added to that chart, and it has gone off the top of the line that we have there, and it is continuing to go up.

Dr. CALVIN. That is right.

Mr. GORE. Now, we are told that decreasing use of oil may make the problem less significant, but you are telling us that the substitution of coal for oil means that 1.7 times as much carbon dioxide will be put into the atmosphere per unit of energy for each unit produced from coal rather than from oil.

Now, let's suppose that the people of this country decide that you are right, Dr. Calvin, and that others in these scientific fields are right. What then would be an intelligent response?

Dr. CALVIN. We would have to use the carbon dioxide that we produce as fast we produce it. That means we would have to learn how to collect it in annual crops to keep it from rising. That is the first thing to do.

The second one would be to go to nuclear power, which does not produce carbon dioxide.

Mr. GORE. Or a vastly scaled-up program for renewable sources.

Dr. CALVIN. Well, that is what I meant. By renewable sources, I mean to use the forests and the growing plants as a source of our energy, because that cycles the carbon through each year, and that is what that chart really is.

Mr. GORE. So what we are really talking about, if our civilization, not just in the United States but in other industrialized countries, if we determine that this is in fact real and determine that the consequences, the dire consequences being discussed, are in fact going to occur, then we would have two choices. We could either try futilely to adapt to these dramatic changes in the space of two generations, which you say would be impossible——

Dr. CALVIN. I think it would be.

Mr. GORE [continuing]. Or we would be faced with a global decision to move rapidly away from fossil fuels and toward solar energy, other forms of renewable energy, and accept an enhanced role for nuclear power.

Dr. CALVIN. Very likely. It is possible to increase the amount of energy we have available from the Sun by means of suitable growing strategies. That is, the wood that we use is actually solar energy captured a year or two or three before.

Mr. GORE. Yes.

Dr. CALVIN. And if we could devise a way of doing that on a big enough scale so that most of our energy would be renewable in that sense, collected from the Sun, either by the trees or by some other method—there are other methods, but the trees are the best way we know today—then we would be avoiding that problem, yes.

Mr. GORE. All right, now, one final question, lest I encroach on my colleagues' time too much. The impact for the entire world you have discussed. The impact for this country, if you just look at this country, the impact is very severe, with the loss of the grain belt, the loss of coastal cities, et cetera. I mean, these things are difficult to even contemplate.

What areas of uncertainty remain? We are not certain that all of these things are going to occur; we are becoming more certain. Is that an accurate way to say it?

Dr. CALVIN. Well, certain; you are quite right. As data accumulate, we become more certain, first, of the facts, and then, having better facts, we make better predictions as to what the consequences of those changes are going to be, and that is precisely what you have said. As we gather more data, we can be more certain that the greenhouse effect, which is a global effect—it is not just the United States; it is a global effect—will ensue.

That temperature rise has many, many severe consequences, a few of which are described in various publications, some of which I referred to in this data, in which the level of the sea will rise because of the melting of the south polar ice cap and things of this kind, if the average temperature is allowed to continue to rise by the continued combustion of carbon which has been stored in the ground hundreds of millions of years ago.

Mr. GORE. Well, thank you.

I think, Mr. Chairman, that the scientific community is crossing a line today, and, whereas in the past they have been telling us that this theory is troubling, they are now telling us that there is physical evidence that the probability of these events occurring is increasing.

Dr. CALVIN. Indeed, yes.

Mr. GORE. Thank you, Mr. Chairman.

Mr. SCHEUER. Thank you, Mr. Gore.

Mr. Carney?

Mr. CARNEY. Thank you very, very much, Mr. Chairman and Professor Calvin.

If you really wanted to demonstrate the problem, I am led to believe that if there was a 15-foot increase in the oceans, all of Washington would be under water, with the exception of the Capitol dome, and that might shake many of us up right here.

But I would like to get to your chart, professor, from "Energy in a Finite World," the chart on the projections if you were to go to a 30-TW solar and nuclear strategy.

Dr. CALVIN. Which chart are you talking about?

Mr. CARNEY. You have the two charts. It is from "Energy in a Finite World."

Dr. CALVIN. Oh, yes.

Mr. CARNEY. I am curious as to why, when there was continual growth in the carbon dioxide emissions, the temperature in 1965 was at one of its lowest points.

Dr. CALVIN. Temperature change is what it says, not the temperature.

Mr. CARNEY. Yes, temperature change.

Dr. CALVIN. The temperature was rising all the time. That was an incremental, per year, change.

Mr. CARNEY. I see.

Dr. CALVIN. That is what that means.

Mr. CARNEY. Well, why would it go down from 1940 to 1965? How come it continually went down?

Dr. CALVIN. The temperature change dropped from—this is the change now, this is not the—it is still going up. It is just that the rate of change has decreased.

Mr. GORE. Will my colleague yield?

Mr. CARNEY. I will be glad to yield?

Mr. GORE. Other scientists have speculated that the rate of increase has been affected by the water that has melted from the ice cap changing slightly the ambient temperature of the oceans as the ice has melted and the temperature of the oceans has changed downward somewhat.

Mr. CARNEY. If that is the case, then, will it balance out?

Dr. CALVIN. No.

Mr. CARNEY. Why not?

Dr. CALVIN. Because as you increase the amount of carbon dioxide in the atmosphere, you increase the amount of heat collected by the atmosphere constantly, and there is nothing to balance it against.

Mr. CARNEY. OK, the amount, the percentage of temperature change from 1940 to 1965 continually dropped.

Dr. CALVIN. Yes; because we were——

Mr. CARNEY. My colleague explains it is because of the melting of the water.

Dr. CALVIN. That is right.

Mr. CARNEY. And that will not reach an equilibrium where then the temperature will not——

Dr. CALVIN. Well, when there is no more ice left to melt, yes, that is right.

Mr. CARNEY. OK, that is the reason? There would be no more ice left to melt?

Dr. CALVIN. If there would be no more ice left to melt. You will be in trouble. [Laughter.]

Mr. CARNEY. What energy alternatives would you suggest to change this around drastically?

Dr. CALVIN. Well, the basic source of all of our energy, historically, and the largest amount of it has been the process of photosynthesis; that is, the process by which the green plants on the Earth's surface collect the sunshine and reduce the carbon dioxide in the atmosphere to reduced carbon, which is, first of all, sugar and then eventually is converted into hydrocarbons, which are laid down as oil or gas.

Now, that is the overall picture. Now, your question, then, is what?

Mr. CARNEY. The strategy——

Dr. CALVIN. What strategy shall we use?

Mr. CARNEY. Absolutely, right. Given the fact that we accept this data and we say we have an enormous problem that we have to react to almost immediately, what is your suggestion?

Dr. Calvin. To continue to use those forms of energy which do not lead to a net increase in carbon dioxide, do not lead to a net increase.

Mr. Carney. Which ones are they?

Dr. Calvin. Well, there are only two, really, that does not do that, one is nuclear.

Mr. Carney. Are you suggesting that we should——

Dr. Calvin. Wait a minute. Solar collection as well. Now, these are solar collections, but these are solar collections using the natural system, which takes the carbon dioxide out of the atmosphere, stores it as sugar or fat or oil, eventually, and then we recombust it.

Now, we have ways of catching the Sun without doing that, and that is another alternative that we have to use.

Mr. Carney. Let me ask you this.

Mr. Scheuer. Will my colleague just for a followup?

Mr. Carney. I will be glad to yield.

Mr. Scheuer. How about other forms of renewal energy, so to speak, like geothermal, biomass, wave, tidal——

Dr. Calvin. Well, biomass is this.

Mr. Scheuer. Yes.

Dr. Calvin. Now, geothermal is not a renewable source. That is the heat of the Earth; it is cooling off. Now, I think we have plenty of time. I do not think it is going to cool off that fast, so I think, in our——

Mr. Scheuer. Well, there is more of it there.

Dr. Calvin. Pardon?

Mr. Scheuer. There is more where it comes from than we are being able to use. That is what I am saying.

Dr. Calvin. A good point, yes.

Mr. Scheuer. Tidal, wave, wind——

Dr. Calvin. That is right. Those are the alternative sources—that is correct—to burning a larger and larger amount of carbon which has been stored over the hundreds of millions of years of geological history. That is the alternative. Is that the question you were asking?

Mr. Scheuer. Yes.

Mr. Carney. From 1860 to the present time, the oceans apparently have risen 75 millimeters. What has been the impact other than what you explained about the slowing of the Earth? According to this chart——

Dr. Calvin. Yes. And what is your question, then?

Mr. Carney. I am saying, from that time frame, there seems to have been, in my mind, a very minimal increase. We are talking about 75 millimeters.

Dr. Calvin. That is 7.5 centimeters. That is about that much.

Mr. Carney. Right.

Dr. Calvin. That means we lost that much coastline.

Mr. Carney. OK, what is the impact of that?

Dr. Calvin. We have lost that much coastline.

Mr. Carney. We have lost that much coastline?

Dr. Calvin. Yes, and that may spread over a great many miles, you know, of beaches. What I am talking about is the depth now, not the——

Mr. CARNEY. I understand. What have you seen as that impact today that I can relate to my constituency?

Dr. CALVIN. We are not talking about things on a human-life scale. We are talking about things on a civilization scale, and you have only lived a fraction of a human life, so you cannot see anything.

Mr. CARNEY. Well, I am asking you to project, if I could live, what would I see? [Laughter.]

Not to project into the future. I am saying, we have scientific data that says the oceans have risen.

Dr. CALVIN. Yes.

Mr. CARNEY. Now, what has that caused? What has been the problem, other than the fact that it is believed the Earth is slowing up, the rotation of the Earth is slowing up?

Dr. CALVIN. Well, you have lost a lot of nice beaches, for one thing.

Mr. CARNEY. Can you identify any of them?

Dr. CALVIN. No; I cannot, because I am not a beachgoer.

Mr. CARNEY. I mean, here we have 100 years of evidence.

Dr. CALVIN. Yes.

Mr. CARNEY. And what has happened? What have we lost? Have we lost any farmland? Have we lost——

Dr. CALVIN. Yes; we have.

Mr. CARNEY. We have?

Dr. CALVIN. Yes.

Mr. CARNEY. Can you identify any of that?

Dr. CALVIN. No; except along the coastlines. I cannot do that.

Mr. CARNEY. You are saying that our coastlines have—

Dr. CALVIN. If the rise has been whatever the number turns out to be, then that much coastline has been drowned.

Mr. GORE. Will my colleague yield?

Mr. CARNEY. I will be glad to yield.

Dr. CALVIN. I am not sure I understand what you are driving at.

Mr. CARNEY. What I am driving at is, we have 100 years of data, and can anybody——

Dr. CALVIN. That is trivial. That is trivial compared to geological time. That does not mean a thing.

Mr. CARNEY. I am simply asking, can anybody identify anything that has been lost to this world over that 100-year period of time?

Dr. CALVIN. Oh, yes. The coastlines have shrunk. Now, I cannot draw you the map because I have not made such a map.

Mr. SCHEUER. How about currently arid areas of the Earth's surface, both in the Southwestern United States and in sub-Saharan Africa?

Dr. CALVIN. Those have been stretching——

Mr. SCHEUER. Would they have been less dry and less arid and more fertile if——

Dr. CALVIN. Well, you are asking the wrong person on this. I will try my best to respond. It is quite obvious that the questions you are concerned about now are questions of detailed global climate patterns, and you need a meteorologist for that. The only thing I can tell you is what has happened to one of the variables; namely, the average temperature, and that has gone up, and that kind of thing will continue and, with its consequences of the melting of the south polar ice caps and the rising of the sea levels, will reduce the shorelines, will change the shorelines materially.

Now, how much has happened in the 100 years, I cannot answer that question, and you will have to get a geologist and a cartographer to answer the kind of question you are asking. I can say this, that the average temperature has already been rising noticeably a few tenths of a degree. That history I have seen.

Mr. **CARNEY**. In the last century, how much has the temperature changed?

Dr. **CALVIN**. A few tenths of a degree.

Mr. **CARNEY**. In the last century, a few tenths of a degree?

Dr. **CALVIN**. Yes.

Mr. **CARNEY**. Well, my bell has been rung, Mr. Chairman, so I yield back the balance of my time. [Laughter.]

Mr. **SCHEUER**. You said a few tenths of a degree, but yet it is expected, in the next 50 or 60 years, to go up between 3 and 7 degrees?

Dr. **CALVIN**. Yes.

Mr. **SCHEUER**. So that is a quantum jump, is it not?

Dr. **CALVIN**. Yes; it is a very big jump. This chart gives you some idea of how much the shoreline has receded. It shows you what the mean sea level change has been from 1860 to 1960. There is a projection of 1980 here. That change has been from 90 to 160 millimeters, the rise has been that much. Well, less than that, from roughly about 70, I guess, somebody said behind me, and I think he is right. I am just taking an average here, up to something over 170, something like that.

Mr. **SCHEUER**. Professor, what you are telling us has some enormously important national implications. We have two national movements in terms of energy production. The first is a sort of "stop, look, and listen" with nuclear. There has been a slowdown in nuclear, and a lot of people think we are not going to be building any more nuclear plants.

The second is a massive push toward conversion from oil to coal on the assumption that we have 500 years or so of coal in the ground, and it is here. There is an urgent national security need to free ourselves of energy dependence upon the Persian Gulf oil and the whims and caprices of a few sheiks in the Persian Gulf area.

So we have two national pushes, one to reduce development of further nuclear for a time and perhaps for a generation or more, and the other, massively to increase our production of coal and utilization of coal, at least for stationary energy users.

Dr. **CALVIN**. Yes.

Mr. **SCHEUER**. Now, what you are saying is that we probably ought to reverse both of these.

Dr. **CALVIN**. If we can.

Mr. **SCHEUER**. You are talking about a change in American energy policy.

Dr. **CALVIN**. Actually, keep in mind that when you burn coal, to get the same number of Btu's, to keep the house at the same temperature, the same house—now, don't change the house on me—but the same house at the same temperature, you have to produce almost twice as much carbon dioxide with coal as you do with oil, and certainly more than twice as much over the use of gas, just to give you an idea. That is a big difference; that is not a trivial difference. It is a very big difference.

Mr. SCHEUER. Professor, the Earth has enough coal under there available to last us a long time.

Dr. CALVIN. That is the trouble.

Mr. SCHEUER. Apparently, we are running out of supplies of economically exploitable petroleum almost everywhere. The Saudis can measure the time in which they will be running out of oil.

Dr. CALVIN. Yes. I have some graphs that will show that, too, but I did not come to testify on that.

Mr. SCHEUER. Yes. Over the long-term pull, can we chart national energy policy for half a century to avoid these devastating effects that are a half century down the road. Is it safe, is it prudent for us at this time to chart a long-term national dependence on petroleum for us and the rest of the developed world, because we are in this together, and if we don't hang together, we are going to hang separately.

Can the developed world, along with the developing world, plan to fuel its industry, its heating, its air-conditioning, its vehicles, through dependence upon oil, when oil seems to be, down the pike, in so much shorter supply than coal?

Dr. CALVIN. My personal reaction to this is that there are ample ways to make ourselves dependent on renewable resources which ultimately, of course, are solar in their origin but not simply to catch the heat of the Sun. Catching the heat of the Sun is the lowest form of catching solar energy. That is catching it in its lowest, cheapest way, not cheapest in dollars but the lowest form.

Catching it as high-quality quanta—that means as sunshine as it comes, as Sun, which the green plants can do—they catch them in quanta that are of the size of, well, they are 60-kilocalorie, 70-kilocalorie quanta, big chunks, and they can do things with those quanta that nobody else can do. No other organism can do it. We still don't know how to do it, how the green plant does it. I have been spending my whole life on that. I know a good bit about it, but I cannot reproduce what the green plant does. It takes the sunshine in its highest form and the carbon dioxide out of the atmosphere, which is what we are fussing about, and makes fuel out of it, first in the form of sugar and then in the form of hydrocarbon, and both of these we can use, and this, I think, is the way we have to go, in which we are making a better use of the solar energy and letting less of it degenerate into heat and using more of it in the form of chemical energy, which is in the form of sugar, which is wood, and hydrocarbon, which is oil.

Both of these things can be done if you spend a little more time at it, give a little more thought about it and a little more money on it.

Mr. CARNEY. Would the gentleman yield?

Mr. SCHEUER. Yes; of course.

Mr. CARNEY. What is a little more time, what is a little more thought, and what is a little more money? Is it 4 years and $10 million; is it 40 years and $30 billion?

Dr. CALVIN. No. Well, now, you have put two variables together which are not compatible. In other words, if you wanted to do it in 10 years, you would have to spend, I would guess, $30 to $40 billion just on that problem alone. There are many others, but that is my guess. The only way I can make my guess—and remember, this is now circumscribed by my personal experience and not by your imagination, which I should hope would be better than mine in this matter.

Do you understand that? I am talking about what we have been able to do in the past, not what could be done in the future. That is your job, not mine.

Mr. CARNEY. Well, that is why you are here, to help us make those decisions. We are asking you what you are talking about in timeframes. I mean, if it is around the corner, then it is something that——

Dr. CALVIN. It is here now on a small scale. If it is going to be done on a scale to avoid the catastrophes we have been sort of walking around, then you have to increase the scale enormously.

The solar energy budget of DOE ought to be doubled, tripled, and quadrupled in the next 6 years if you expect to avoid the catastrophes we are talking about.

Mr. CARNEY. How about the budget for nuclear energy with DOE?

Dr. CALVIN. That has another problem.

Mr. CARNEY. What is the problem?

Dr. CALVIN. I am not going to testify on the problems of nuclear energy. You can get somebody else to do that. [Laughter.]

I am concerned about it. Believe me, I am concerned, but I am concerned as a lay person. Do you understand that? I have worked with it. I know something about it.

Mr. CARNEY. You are saying that if we went to nuclear power, we would alleviate some of the problems with the carbon dioxide situation, but you are not particularly supporting nuclear power.

Dr. CALVIN. You would have other problems, much bigger ones. [Laughter.]

Mr. GORE. If my colleague would yield, so what you are telling us——

Dr. CALVIN. Mr. Carney, don't you like that?

Mr. CARNEY. No, no, I have no problem at all with what you are saying. That is why we asked you to come here.

Dr. CALVIN. OK.

Mr. CARNEY. I am just curious, in timeframes, you have not identified a timeframe——

Dr. CALVIN. I have, too.

Mr. CARNEY [continuing]. To when we can apply the technologies necessary to use I guess what you would call a biomass technology.

Dr. CALVIN. It is a biomass technology. It is a combination. Let me tell you what that is, if you will excuse me, sir.

We use the biomass as such to produce wood and oil. Some plants produce oil. We could use the information of how the plants do it to dispense with the plants entirely and build synthetic devices that can do it, that can catch the Sun and store the energy in any way you want it. There are two different ways. This really is not the forum for this—I understand that—but now that you have opened it up for me, I cannot avoid it.

Mr. SCHEUER. It is the forum.

Mr. **Carney**. We do everything here in a very informal way, professor. Just carry on, no problem. [Laughter.]

We are trying to learn something.

Dr. **Calvin**. Let me tell you, we have, for the whole history of the human race, depended upon the ability of green plants to catch the Sun and convert it into useful forms. The useful forms have been food for people and energy to keep warm and to run our machines. Those are the things we have been able to do.

Now, what I am trying to tell you is that as we learn how the green plants can do this—and we have learned a great deal in the last 20 years, believe me, a lot—the time is coming when we will be able to replace the green plant with a totally synthetic device, manufactured—I can do it, almost do it today—which will do part of that. We will not be able to make wood, but we will be able to make a useful form of energy which can be stored in a tank for as long as you like, and this will not involve arable land.

Mr. **Scheuer**. Are you talking about gasohol?

Dr. **Calvin**. No. Well, that is one possibility. That is using a plant to make sugar and then convert sugar to alcohol.

Mr. **Scheuer**. What are you referring to, specifically?

Dr. **Calvin**. I am referring to the direct conversion of solar energy into useful fuels, and we know how to do some of that on a small scale.

Mr. **Scheuer**. What do you call those fuels?

Dr. **Calvin**. Hydrogen, for example.

Mr. **Scheuer**. Right. Go ahead; I am sorry.

Mr. **Carney**. I appreciate what you are saying, but there is a little catch 22 there. When will we be able to apply those technologies, and will we be able to apply those technologies before the carbon dioxide problem gets totally out of hand?

Dr. **Calvin**. If you get off the dime, we can apply some of them today.

Mr. **Carney**. To what extent?

Dr. **Calvin**. What do you mean by what extent?

Mr. **Carney**. To what extent can we apply it?

Dr. **Calvin**. Can we replace the whole energy demand of the United States?

Mr. **Carney**. I am not saying that.

Dr. **Calvin**. Well, that is what I am asking you.

Mr. **Carney**. I am saying, can we provide it for our transportation needs? Can we provide it for domestic heat? Can we provide it for industry?

Dr. **Calvin**. How long are you going to give me and how many dollars are you going to give me? [Laughter.]

Mr. **Carney**. That is the question, sir. Professor, that is the question I have asked, and that is the question you have been avoiding. How much do you need and how soon can you apply it, and can we beat the problem? Or do we have to go to some technologies that are available today, mainly nuclear?

Dr. **Calvin**. No. There are some technologies—well——

Mr. **Carney**. What is "well"?

Dr. **Calvin**. Well, wait a minute.

Mr. **Carney**. I mean, come on. [Laughter.]

Dr. **Calvin**. You are a Congressman; I am not, and I am not used to doing what you are doing, and I have to learn. I have to learn from watching you.

Mr. **Carney**. Professor, you are doing a great job. [Laughter.]

You have not answered my question yet. You are a better politician than anyone else sitting here. [Laughter.]

Dr. **Calvin**. There are some of the things we can do right now, you know. We can make hydrogen today with light from the Sun. Suitably built devices can be done. I would like to go further. I would like to make methane, natural gas, that way. I don't know how to do that yet, but I would like to. That is one of the things I would like to do.

If, for example, the solar energy budget is a wide-open thing. I don't like to use that word because it covers the waterfront, you know. It covers just that, the waterfront—hot water heating, for example. That is not what I am talking about. I am talking about quantum conversion, catching the light in its highest form, not down in its lowest form as heat, but as light, and having that light move electrons around so that I can generate useful fuels such as hydrogen or methane, natural gas, or something like that. I can do that. I can do the hydrogen today. I could do the natural gas, say, in 10 years or less.

Now, you are asking me how big has the budget got to be. I cannot answer that because I do not know how big the budget is today. I am not working for DOE. Well, I am working for DOE but at the bottom of the pole. [Laughter.]

So I don't know what is going on up here.

Mr. **Scheuer**. Well, the record should show——

Dr. **Calvin**. You understand what I am saying? That is why I cannot answer your question in detailed numbers, but if you wanted them in detailed numbers, I think it could be done. I think it could be done within a decade or two if I were not constrained to come to Congress and beg for the dollars every year.

Mr. **Carney**. Well, Mr. Chairman, my bell has rung twice. [Laughter.]

I appreciate your patience, Mr. Chairman, and I thank you, Professor.

Mr. **Scheuer**. Professor, you are on the Energy Research Advisory Board of the Department of Energy.

Dr. **Calvin**. Yes.

Mr. **Scheuer**. So you have more than a passing familiarity with their work. Your recent report of this Advisory Board put energy research into the carbon dioxide effect on the very highest priority, right at the top of the pile in terms of the vital importance to our country and our security and our future.

You advocate increased funding to the Department of Energy this year. We authorized $17 million for research into the greenhouse effect. We gave them an appropriation of $12 million. The administration now is only asking for $8 million, which is $4 million less than has been already appropriated and $9 million less than what we authorized last year. They must think that we are spending far too much on this greenhouse effect. They must be thinking, well, let somebody else worry about it 10, 20, 30 years down the pike.

Dr. **Calvin**. Too late then.

Mr. **Scheuer**. All right. Now, this is a time of constraints on all kinds of spending. We are not giving kids the food they ought to have at lunchtime. We are cutting down on programs for maternal and child health. So this program has to compete in rational terms with other very important programs that we are underfunding.

You have heard my colleague from Pennsylvania express intelligent fears that we are doing too much, too fast, in terms of research into this project.

Mr. **Walker**. If the gentleman would yield, I don't think that is the point that I made. I am sorry the gentleman took that point because that was not the point that I made at all.

Mr. **Scheuer**. Well, you think the program should be substantially terminated, that we know enough to go ahead.

Mr. **Walker**. That is not the point that the gentleman from Pennsylvania made at all. The gentleman from Pennsylvania simply said that I have seen the same research presented here over and over again, and the question is, when do we use research in some practical way——

Mr. **Scheuer**. That is right.

Mr. **Walker** [continuing]. And whether or not the money shouldn't be devoted in that direction rather than in this direction. So I don't want the gentleman to misinterpret what I was saying. I was simply saying that once we have the research in place, there may be better uses for the money as we look toward the future.

Dr. **Calvin**. Can I ask him a question?

Mr. **Scheuer**. No; let me ask the questions.

Mr. **Walker**. I am hoping that at some point, Professor Calvin, I will get a chance to participate here.

Mr. **Scheuer**. You will, just as soon as I am finished. [Laughter.]

Dr. **Calvin**. I don't know what you would ask.

Mr. **Scheuer**. Professor, the question that we now get to is, what do you recommend specifically in terms of a research budget addressed to this problem of the greenhouse effect, and over what period of time? What could be done that would give us, sufficient information to justify a major ongoing energy production program? Is there some plateau that we could reach? Is there some critical mass of information, knowledge base, that we could reach that would give this committee the means of recommending practical, major energy production programs that would be consistent with the survival of the planet?

Dr. **Calvin**. Well, first of all, I have to back up a little bit and point out to you that that data on that curve that you have seen, this greenhouse effect, this up-and-down curve, which is the product of one researcher, or one major researcher, Dr. Keeling, at San Diego, at the Scripps Institution down there; one station at Mauna Loa has given us that, and it has been used all over the world, not only by us but by the British and the Russians and everybody else.

We need half a dozen stations like that, as good as that, all over, and different kinds of places. When I first saw that curve, I called Dr. Keeling, and I said, Look, why don't you set one up in Manaus, you know, in the middle of the Amazon forest? Well, he is a geophysicist. He said, "I shouldn't do that. The forests will disturb the measurement." I said, "That is what I want to find out." I want to find out does the forest suck up the carbon dioxide or not. This is on the top of a mountain. That is the kind of data we don't have.

Now, that means stations like that in various places. I cannot tell you the cost, obviously, and that is not my business. But we need that kind of information. We need better information about the carbon dioxide sinks in the ocean. Those are the two major sinks, the green stuff on the surface of the planet and the oceans themselves, and we need both in order to find out where is it going. We know approximately where it is coming from, but we don't know how it is getting out. I mean, where is it going and at what rate, and what are the limiting things? What do we have to do to increase it in order to prevent that problem, you see?

That is what I mean when I say we need more, but if you ask me how many more dollars, I can't tell you that; I don't know. Does that answer your question?

Mr. SCHEUER. Well, that it is an answer; but not the answer; to the question we were asking.

Dr. CALVIN. What answer did you want? Dollars?

Mr. SCHEUER. Yes. We are looking for a program. What do we have to know that would give us the knowledge base to justify the kind of energy production programs that would be environmentally benign.

Dr. CALVIN. Well, we have to know, first of all, where is this all coming from? That means stations all over the globe, not just in the Mauna Loa. We have one measurement in Point Barrow, Alaska. We have one in the South Pole, not a very complete one like that. We have a few other sites here and there. The Swedes have sites. But Keeling's is by far the best data we have, and if we had two or three more like that in different latitudes, we would have a little better sense of where it is coming from and where it is going.

Mr. SCHEUER. Congressman Walker?

Mr. WALKER. Thank you, Mr. Chairman.

First of all, I think you rather properly admonished me with regard to Pennsylvania coal. I would say that in my district, though, we are more in the process in my district of useful photosynthesis in the agricultural area rather than the coal area.

Dr. CALVIN. I am speaking of the 19th century.

Mr. WALKER. But I would come back with another admonishment that maybe if the nuclear option needs to be preserved in order to do something about this problem, maybe the scientific community ought to help us get some money in to help clean up the problem at Three Mile Island so that that nuclear option can be preserved.

Dr. CALVIN. That is impossible.

Mr. WALKER. You, I think, have made some rather important contributions here today. It seems to me that we are faced with something that, over the long term, could produce some catastrophic consequences and that we need to evaluate it in those terms, and that that calls for a balanced energy policy of some sort, but a balanced energy policy that takes this kind of a problem into account. Too often, I am afraid that we are not doing that.

For example, there has been much criticism within this committee, and some of the criticism I share, that this administration is pursuing the nuclear option to too great an extent. But it seems to me, based upon the testimony you have given here today, that there can be some pretty good scientific data to back up precisely that kind of direction. It might not be what everybody wants to do, but in terms of this problem, there is some pretty good scientific data, and in fact even we would have to admit that Europe is pretty well ahead of us in moving in this direction as a part of their energy option. Isn't that true?

Dr. **Calvin**. Let me point out to you that nuclear power produces only heat. It does not directly produce liquid fuel. Our country runs on liquid fuel, and you know it.

Mr. **Walker**. Absolutely.

Dr. **Calvin**. Therefore, my concern is that we have to find a way to fulfill that need. Otherwise, we become a different country. And that need can only be filled by biomass properly adjusted, and that is what I am after, not nuclear power.

Mr. **Walker**. I don't disagree with that, and I think that there has to be some balance in it. What I am saying, though, as it seems to me, from this kind of scientific testimony, that preserving the nuclear option as a part of the baseline loads that we need, for instance, for electricity, is important.

I happen to agree. I think you mentioned a few minutes ago the hydrogen option. I think if we looked into the 21st century that we had better be concentrating toward the hydrogen option, particularly for mobile sources of power.

I really understand what you are saying there, and I think a conversion—but again, it is going to take some sense of balance, and insofar as we cancel out elements of that balance and ignore this kind of data as we cancel those things out, I think we do a great injustice to our future attempts to make some significant gains in real energy development.

Dr. **Calvin**. Precisely, and I think—I don't know who is doing it—but the Congress is cancelling out the liquid fuel option from biomass. They have done it in the last 2 years, and it seems to be going still further, and that is what I am fighting for, in case you haven't recognized it, and not for nuclear power. That is a different matter. That produces a different kind of energy, a different way of using the system.

We need liquid fuel, and we need it on a very large scale. The only way I can see of getting it is from biomass. That is the only way—renewable. I am not talking about digging it out of the ground.

Mr. **Walker**. Well, we would probably be in some degree of agreement on that point. The point I am making, though, is if we just take the hard evidence that we have been presented with regard to the greenhouse effect, I think you have to admit that one portion of meeting that particular problem is to in fact use nuclear.

If you are concentrating on just this problem, that nuclear may present a whole range of other problems, and believe me, I know that it does. I have got one in my back yard—so that I have some reservations about that, and I am perfectly willing to express those, but if we use this scientific evidence, it seems to me that we cannot then ignore the nuclear option as well. Isn't that true?

Dr. **Calvin**. I am not arguing to ignore it. I am saying it will not produce what we need. What we need are liquid fuels for our present society, and nuclear will not do that, and the only way we get that is biomass.

Mr. **Walker**. Liquid fuels are obviously an important part of what we are doing——

Dr. **Calvin**. Wait a minute. Let me finish.

Mr. **Walker** [continuing]. But I am saying to you that in terms of the infrastructure which is in place right now, our power needs, nuclear does provide one portion of the power that is needed within that present infrastructure. Isn't that true?

Dr. **Calvin**. It provides electric power.

Mr. **Walker**. It provides electric power.

Dr. **Calvin**. That is all.

Mr. **Walker**. OK. That is one element of the whole. Now, we also need a very strong concentration on liquid fuels as well, particularly because we are dependent upon liquid fuels, as you put it, in our infrastructure of pipelines and all of this kind of thing, and obviously in our mobile sources of energy need.

But what I am saying to you is that if we take this scientific data, which you have said produces catastrophic consequences if we ignore it, then nuclear as a portion of that would seem to have some relevance. Isn't that true?

Dr. **Calvin**. Well, I cannot argue against that, naturally; it has some relevance. It does not produce liquid fuels or gaseous fuels.

Mr. **Walker**. OK, but you have also made the point that carbon dioxide produced from burning coal—is done for electrical power.

Dr. **Calvin**. That is right.

Mr. **Walker**. I mean, in other words, insofar as we are burning coal, the vast portion of it is being burned for electrical power, and so what we are looking at, we have to look for alternatives in that particular area. Isn't that true?

Dr. **Calvin**. All right, let me suggest an alternative, and I meant that in the back of my mind when I referred to you in the first place. It is possible to take the carbon dioxide out of the stacks, at a price. It is possible. So you can burn coal and burn it cleanly, take away the carcinogens which it produces—that is really perhaps the worst part of it—take out the ash, remove the carbon dioxide, condense it into solid dry ice and drop it in the bottom of the sea. It can be done if you are willing to pay the price.

Mr. **Walker**. Well, and that is true, and one of the things that we have always got to be concerned about is, at what price is that.

Dr. **Calvin**. That is right, and I think the price for that is less than the price for nuclear waste disposal on the moon. [Laughter.] I mean, that is the alternative, as far as I am concerned.

Mr. **Walker**. That may well be, and one of the reasons why we have to be concerned about the nuclear option at the present time is the expenses of all kinds in it.

Dr. **Calvin**. Yes.

Mr. **Walker**. But, on the other hand, the kinds of things that you are talking about here would be very expensive options in the coal area as well, so that I do not think that we can ignore, at the present time, when we are deciding on energy options, what maybe those options necessary to get us this kind of scientific data. Isn't that true?

Dr. **Calvin**. Congressman Walker, can I respond now in a little bit more detail?

Mr. **Walker**. Sure.

Dr. **Calvin**. I cannot agree with you more. You have to consider all the options in that sense. You must not close arbitrarily any single one of them. But you have to weigh the relative merits, costs, both in money and in environmental problems, in each of them, and that is really what I am talking about when I say that we can fulfill the electrical power problem with coal if we add to it all these other factors which cost money to do. I mean, you are not going to get the CO_2 out for nothing. The carbon dioxide may have a value all its own besides the small degree value which we have not really considered yet. In fact, the whole chemical industry, if you could hand them tank cars of dry ice, they could begin to build a chemical industry on it, believe me, and so there is a way to make up the costs.

So you do not have to have nuclear power. You do not absolutely have to have it. That is really what I am trying to say, that is all.

Mr. **Walker**. And, as I say, I appreciate that point, and certainly the economics of it, the safety of it are all subject to questions, but I think that sometimes we have proceeded willy-nilly on some of these things to say that nuclear is bad, so therefore we are going to go to some other sources which may also have some deleterious effects as far as the environment, economy, and that which we have not yet assessed goes.

I think maybe the importance of bringing some of this evidence to the forefront and why these hearings are useful, even if I question whether or not we have to go over the same research over and over again, is that these hearings focus public attention on some serious problems that exist in places other than nuclear, petroleum, and other energy industries where we have attempted to identify the problems clearly and propose solutions in some cases.

Dr. **Calvin**. Well, may I just conclude about the relative merits and the hazards of the two alternatives, coal versus nuclear hazard.

The coal hazard, the carbon dioxide hazard, can be eliminated if you stop it from 1990 to 2025. That is about 35 years, and the carbon dioxide is back to normal, by normal processes. You cannot eliminate radioactivity at that rate at all. You are in the thousands of years, and that is the difference.

Mr. **Walker**. Let me ask you to give us some opinion, also, because I think this is important for our evaluation. The bell has rung and I will stop then. What are, over the long term, the relative catastrophic consequences between the two. If you were producing an equal amount of energy with nuclear and an equal amount of energy with coal, what are the relative catastrophic consequences that we could expect from the two?

Dr. **Calvin**. I cannot answer that, Mr. Walker, obviously. I did not come prepared to answer it. I could, but you did not ask me to, and I cannot do it off the cuff.

Mr. **Walker**. Well, if you could supply it for the record, I think it would be very important for this committee to know.

Dr. Calvin. I cannot do it off the cuff because it involves many factors which I do not have in my head.

Mr. Walker. Well, could we ask you to supply it for the record for the subcommittees?

Dr. Calvin. I will try to do that. I will do my best.

Mr. Walker. Fine, thank you. I appreciate it.

Thank you, Mr. Chairman.

[The information follows:]

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DEPARTMENT OF CHEMISTRY BERKELEY, CALIFORNIA 94720

April 22, 1982

Congressman James H. Scheuer
Congressman Albert Gore, Jr.
Committee on Science & Technology
U.S. House of Representatives
Suite 2321 Rayburn House Office Building
Washington, D.C. 20515

Gentlemen:

In response to the question raised by Congressman Walker after line 1615 in the testimony of the hearing of March 25, 1982, I asked Dr. Elton M. Cairns, Director of the Energy and Environment Division of the Lawrence Berkeley Laboratory, to undertake to provide the answer. I have received from him the enclosed document, together with the actual names of the people who undertook the study.

In summary: It appears that both nuclear and coal have environmental consequences of some magnitude. The primary coal problem, of course, is the CO_2 found as 2300 tons per gigawatt year. The primary emissions from nuclear would be about one-half million curies of krypton-85 together with several billion curies of fission products and actinites separated in the reprocessing which would have to be stored for several thousand years.

I trust that you will be able to insert this document in the proper place in the testimony.

Very truly yours,

Melvin Calvin

Melvin Calvin
University Professor

MC:mt
Enc

CC Dr. Elton M. Cairns

4/22/82

ISSUES SURROUNDING NUCLEAR AND COAL POWER PRODUCTION AND THEIR HUMAN AND ENVIRONMENTAL IMPACTS

The environmental and human consequences of greater use of coal and nuclear power have been the subject of a number of recent studies. The issues generally identified range from very specific impacts of mining and thermal pollution, for example, to broader questions of global climate modification and the spread of nuclear weapons. Comparing the known and potential consequences of the coal and nuclear fuel cycles is an exceedingly difficult task, obscured by subjective judgments about global political and social issues, uncertainties in dose-response relationships, and questions about the availability and costs of technologies to ameliorate or resolve specific categories of impacts.

In a report entitled Nuclear Power Issues and Choices, sponsored by the Ford Foundation and administered by the MITRE Corporation, an attempt was made to compare energy technologies in terms of human impact. The general conclusion is that given uncertainties in estimating human morbidity and mortality resulting from exposure of segments of the population to nuclear and non-nuclear accidents and to routinely emitted radioactivity or combustion-generated pollution, there is no clear advantage for nuclear or coal. Since the time the report was published there has been greater focus on a few issues in large part because of either their large regional or global potential impact on man and the environment.

The issues can be placed in three general categories--emissions and impacts resulting from normal operation of the fuel cycle; potential impacts due to accidents; and the national and international issues and consequences associated with nuclear proliferation and global climate modification (CO_2 or ^{85}Kr).

The unresolved issues surrounding nuclear energy are the consequences of a major nuclear accident, nuclear waste storage, and nuclear proliferation. Radioactive nuclides will decay with time; however, a typical timescale for significant reduction of fission products and actinides produced in a reactor is several hundred years. Even with reprocessing, Pu isotopes remain in the waste, requiring isolation for considerably longer periods of time to minimize potential impacts. Recently it has been realized that trace metals in the reactor structure such as ^{59}Ni ($7.5x10^4y$) and ^{94}Nb ($2x10^4y$) will be formed and keep decommissioned reactor structures at significant radioactive levels possibly requiring dismantling and long-term storage in a geological repository. The processing of radioactive waste either for storage or recovery of plutonium could release 500,000 Ci of ^{85}Kr (10.8y) per 1000 MWe-year of reactor operation. Most of the noble gas ^{85}Kr would be released into the atmosphere and would presumably be dispersed globally. There has been some concern that the gas which emits ionizing radiation could modify cloud formation and thereby the weather patterns through modification of the charge distribution in the atmosphere. Although this is a highly speculative concern, the use of radioactivity to charge and discharge atmospheric aerosols is well known and world-wide increase in nuclear power production to 1000 gigawatts with subsequent release of Krypton 85 would increase atmospheric ionization levels by 10%.

The issues of nuclear proliferation and the adequacy of international fuel cycle safeguards has not been addressed here. Clearly they are related to recent public concern and discussion. The Israeli attack upon the Iraqi reactor complex and continuing allegations about loss and possible diversion of strategic material in this country raise anew questions about the adequacy of institutional safeguards for nuclear materials.

The environmental and human consequences arising from the use of coal are largely related to the direct emissions and impacts of the fuel cycle and to some extent, the global concern about CO_2 buildup. A coal-fired production plant will release over 6 metric tons of SO_2 and NO_x, as shown in the accompanying table, and .1 to 1 metric ton of particulates to the atmosphere per Gigawatt-year of energy produced. The total amount of CO_2 released is about 2,300 metric tons for the same energy produced, assuming 12,000 BTU/lb coal. The SO_2 and NO_x are transformed into sulfuric and nitric acid resulting in regional acid precipitation. Approximately one-third of the CO_2 released remains in the atmosphere. As a result, doubling in the CO_2 concentration is possible over the next forty years, resulting in an average rise in the global temperature of 3°-4°C. This temperature change can be expected to bring major climatic changes. Analogous to radioactive decay the CO_2 concentration might be expected to return to its present concentration with time and provided there is simultaneous reduction in CO_2 emission levels. The ocean is the major sink for CO_2 but the time scale for 50% reduction of the additional CO_2 level is a few thousand years. The biosphere is another important potential sink for CO_2, but since forests make up the majority of this reservoir the turnover time for CO_2 is approximately 40 years. More importantly since the total capacity of the reservoir is roughly equal to the amount of carbon in the atmosphere as CO_2, a doubling of the atmospheric CO_2 concentration would require a commensurate doubling in the world's forests to bring the concentration back to present levels.

The emission of submicron size particulates from combustion sources, especially coal combustion, may be at least as important a problem as CO_2, SO_2 and NO_x emissions. There is a significant fraction of the coal particulates in the submicron region. These particles are difficult to precipitate or filter from the coal combustion gas and will end up in the atmosphere. These small particles contain traces of arsenic, mercury, selenium, radioactive thorium and radium. The particles, because of their size, can penetrate deep into the lungs. A large part of the particulate aerosol in urban environments has also been shown to be carbonaceous in nature.

Researchers at Lawrence Berkeley Laboratories in collaboration with the Geophysical Monitoring for Climate Change program of N.O.A.A. have discovered that the Arctic region is polluted with large concentrations of black soot particles similar to the soot found in urban air. The concentrations of the particles in the air and the snow are surprisingly large with the level approaching those found in cities across the United States. For example, during winter and spring the concentrations are only a factor of 3-4 less than the average values found in Berkeley, California; Denver, Colorado; and Gaithursburg, Maryland, and only a factor of 10 lower than that found in highly polluted New York City. These particles are very effective absorbers of the sun's radiation and may lead to a large heating effect over the polar ice cap which could significantly enhance the expected heating due to doubling of CO_2.

The size of this effect is presently unknown due to uncertainties in the vertical and horizontal distribution of these particles. However, calculations done at Berkeley and preliminary computer modeling done at Lawrence Livermore Laboratory indicate that these particles could produce a heating effect in the Arctic region that is comparable to that expected from doubling the CO_2 concentration. This suggests that the climatic effects from the burning of fossil fuels may be considerably larger than if one considers the greenhouse effect of CO_2 alone.

In surveying these issues, particularly with regard to expectations of future impacts, this discussion has extrapolated from present economic and technical practices. It should be recognized that changes in these practices can occur, either due to technological and economic choice or by policy. For example, control of emissions from the burning of fossil fuels has become more stringent with the revision of the New Source Performance Standards in the late 1970's, which will change the predicted human and environmental consequences. Similarly, a major cause of public health impacts in the coal fuel cycle are railroad grade-crossing accidents. Certainly it is technically possible to require rebuilding most of these crossings to a higher standard of public safety.

Likewise, some of the impacts associated with the nuclear fuel cycle can be addressed, such as the trapping and storage of ^{85}Kr and ^{3}H releases. As another example, building nuclear power plants (or reprocessing facilities) near present or future population centers can be discouraged legislatively.

Looking ahead to the next 50 years both nuclear and coal energy production have the potential for major if not catastrophic impact on a large segment of the human race and its environment. At best recovery times are roughly comparable and on the order of 100 years. While the potential for large-scale exposure of humans to radioactivity already exists, there is also apparently a great deal of momentum building toward a significant global climate change.

Henry Benner
Ted Chang
Roland Otto
Hal Rosen
Richard Sextro

jro

EMISSIONS/GIGAWATT-YEAR PRODUCTION

	RATE	
EMISSION	NUCLEAR	COAL
Radioactive Emissions to Atmosphere (Ci)		
^{85}Kr (10 yrs) (with reprocessing)	300-50,000 (500,000)	negligible
Xe		negligible
^{3}H	100-1,000	negligible
^{129,131}I	.01-.03	negligible
^{14}C 3000 yrs.	8	
Th,Ra (Ci)	negligible	15-45
Radioactive Solids and Liquids Waste (Ci)		
Fission Products & Discharge	4x10^{9}	negligible
Actinides	1.2x10^{9}	negligible
Cladding and Structural Materials 10^{4} yrs.	4x10^{6}	negligible
Non-Radioactive Emissions to the Atmosphere+ (metric tons)		
CO_2	negligible	2,300
SO_2	negligible	6-14
NO_x	negligible	6-14
Particulate	negligible	0.10-1.3
Hydrocarbons	negligible	.2-.6
CO	negligible	2.1-2.5
Non-Radioactive Solids and Liquids		
Ash	-	1x10^{5}
$CaSO_4$ sludge (scrubber)	-	3x10^{4} - 7x10^{4}

+ Under New Source Performance Standards

Mr. **Scheuer**. We will hold open the record for a week or 10 days. Also, I would ask unanimous consent, Congressman Walker, that any members who have further questions may be permitted to submit them in writing, and we will hope the witness has a chance to answer them.

Congressman Volkmer.

Mr. **Volkmer**. Thank you very much, Mr. Chairman.

I would just like to go back to some what I call elemental parts of this problem——

Dr. **Calvin**. Good; I like that.

Mr. **Volkmer** [continuing]. So I can understand it better. That is, the carbon dioxide that is in the atmosphere—as we know, the Earth rotates. Does that carbon dioxide in the atmosphere rotate with it?

Dr. **Calvin**. Yes.

Mr. **Volkmer**. Basically along with it?

Dr. **Calvin**. Yes.

Mr. **Volkmer**. And the regional carbon dioxide——

Dr. **Calvin**. Is very quickly dissipated and it is global. The problem is global.

Mr. **Volkmer**. It is global? That is what I am trying to get to.

Dr. **Calvin**. Yes; it is a global problem.

Mr. **Volkmer**. Because of the winds, et cetera, that move it?

Dr. **Calvin**. Yes. It is a global problem, sir. There is a slight difference between the Northern and the Southern Hemisphere because the atmospheres of those two regions do not mix as quickly as they do latitudinally, but that is a small difference.

Mr. **Volkmer**. All right. Now, why do we refer to the Antarctic and not the Arctic?

Dr. **Calvin**. I have to qualify this, Mr. Chairman. I am not an oceanographer; I am just a chemist. My understanding is that most of the Antarctic ice sits on dry land, on the continent of Antarctica, but most of the Arctic ice is floating. That means that if you melt Arctic ice, you don't change the level of the sea. Does that answer your question?

Mr. **Volkmer**. Yes. That is why we basically studied it more than the other.

Dr. **Calvin**. Yes. I am not sure that that is absolutely correct, but I think it is.

Mr. **Gore**. Will my colleague yield?

Mr. **Volkmer**. Yes.

Mr. **Gore**. The way it was explained to me is, if you have a martini glass and you drop a new ice cube in it, then it comes over the edge. But if you have an ice cube already in it and it melts, then the level does not change.

In the Arctic, the ice cube is already in the liquid. In the Antarctic, the western Antarctic shelf is not on land but lifted off of undersea rock beds, sort of undersea islands,

Dr. **Calvin**. Well, it is on land, then. It is sitting on the Earth. It is not floating.

Mr. **Gore**. That is right, so that when it melts——

Dr. **Calvin**. That is all I said, yes. Go ahead, sir.

Mr. **Volkmer**. All right. The other thing I would like to make, understanding those things, is I agree with you. Perhaps, as far as

I am concerned, one of the most relevant things that has been said here all morning is the fact that we need more stations like this. That, in my opinion, would mean, though, some international cooperation.

Dr. **Calvin**. Very easy. I can answer that. Do you want me to?

Mr. **Volkmer**. Yes.

Dr. **Calvin**. About a year ago, I was a guest of the Government of Brazil. One of the questions they asked me was, if was I concerned about the cutting down of the Amazon forests. I said I was because it represents one of the largest primeval forests we have left on the surface of the Earth.

And then the conversation went a little further. Would it be possible to collaborate in the establishment of a carbon dioxide measuring device in several points. At least one point, but I would prefer several points—in the Amazon forest to get some idea of the vertical gradient of carbon dioxide down into the trees. You know, that Amazon forest is huge, and if we could put several of these stations right above the forest—in fact, if we could have a vertical set of stations on 1,000-foot wire or a 2,000-foot wire, you understand. If we have little mass spectrometers on them, we could see the carbon dioxide flowing down into the green stuff of the forest, and have a better measure of how the stuff is being sucked up by the forest. They like that idea, but they do not have the technology to do it. They are quite willing to provide the underpinning for such a station if we would provide the technology.

Now, I am not in a position to make that negotiation, but that is the kind of thing that they are anxious to do. They are concerned, they really are, and they have their own environmentalists who are telling them, you cannot cut down the Brazilian forests. You cannot destroy our source of oxygen, they tell us. It is not quite that bad, but it is bad enough.

They are anxious to do it, I can assure you that, and there are other parts of the Earth in which such cooperation can be obtained with the greatest of ease. In other words, the underpinnings—what do you call it?

Mr. **Scheuer**. Financial?

Dr. **Calvin**. No; the financial part isn't the problem. It is the understructure that you need in order to get these things done. The United States cannot do the whole thing. I mean, we cannot send in everything. We can only send in the station and the monitoring of it, and they will have to build the railroads and stuff like that. You know what I am talking about.

Mr. **Gore**. Infrastructure.

Dr. **Calvin**. Infrastructure. I said understructure; it is infrastructure. Thank you. And they are willing to do that. Yes.

Mr. **Scheuer**. With joint scientific input?

Dr. **Calvin**. Yes, of course, of course. They are very anxious to do that.

Mr. **Volkmer**. You say the Swedes are doing some monitoring?

Dr. **Calvin**. The Swedes have made separate airplane flights over the northern regions of their country, with the view of measuring carbon dioxide there. Those flights are made quite on a regular time basis, and they keep track of them pretty well. That has been going on for at least a dozen years. Those are not stations in one place, and therefore the data are not as good as this. This is really first-class data, this stuff. But that is the kind of data we need more of, and similar data on the oceans at depth. There is a little more of that available. It is not as nice as this because it moves around, but that is what I would like to see. And I think we can get the cooperation. I don't think there is any problem about that.

The only thing that worries me about this, not about the carbon dioxide cooperation, is that the three biggest coal-burning countries in the world, the three biggest coal supplies in the world, are the United States, the Soviet Union, and mainland China, and I don't know how much cooperation we are going to get on those things. I cannot answer that. You folks would maybe do better at that than I.

Mr. **Volkmer**. And they are basically in the same areas, I mean the wind—they are latitudinal.

Dr. **Calvin**. Yes; they are in the Northern Hemisphere. That is correct, yes.

Mr. **Volkmer**. The other point I would like to make after listening to this discourse is to how do we resolve the carbon dioxide problem when we use coal. I foresee that coal will continue to be used not only in this country but throughout the world, within the next 20 to 30 years, as a primary source of energy. I do not think that we are going to be able to change that drastically on the financial aspects of the problem.

Dr. **Calvin**. I have, of course, the same trepidations that you have just expressed. I hesitate to say them out loud because I don't know the details of them. I did, as you heard a moment ago, mention the other two large sources, and it is quite obvious that our influence on those sources is not going to be very profound.

And so, what we do can be useful, I think, only by example, primarily, and not per force. Does that make sense to you?

Mr. **Volkmer**. Yes.

Dr. **Calvin**. But if we do not do it, then there is no hope at all. That is really what it comes down to.

Mr. **Volkmer**. But even if we do it and others do not——

Dr. **Calvin**. But if we do it, there is a hope. That is my point of view on it. If we don't do it, there is absolutely no hope at all.

Mr. **Volkmer**. Thank you very much, Mr. Chairman.

Mr. **Gore**. Thank you, Mr. Volkmer, and Dr. Calvin, thank you very much.

I would like to note at this point for the record that, in my opinion, this problem will become more difficult to face and resolve if we began fighting between different successor fuel sources. Each of us has our notions on which direction we could go, and what is viable.

I note for the record that the solar budget is being reduced from $552 million to $72 million; geothermal, from $156 million to $9.8 million; hydropower, from $3.2 million to zero. There is ample room for argument on all these sources, and this is going to challenge the political ability of civilization as it has never been challenged before, if your predictions are accurate.

Thank you very much for joining us this morning. I might also note for the record, Dr. Calvin, although you said you were learning how to ask questions from example, I am informed on good authority from a sophomore chemistry student that you have had plenty of practice in asking tough questions.

Dr. **Calvin**. Yes; 40 years. [Laughter.]

Seriously, one last comment, Mr. Gore. I would not put, I would be careful about putting, all the alternatives in the same boat on this problem, because they are really not in the same boat. They don't have the same accessibility; they don't produce the same consequences.

And so your concluding statement, putting them all together, bothers me a bit because they really are not in the same boat. Please keep that in mind.

Mr. **Gore**. I will, and I personally strongly favor your suggestion that we have a massive increase in biomass programs and adopt the synthetic photosynthesis that you are recommending for this country.

Dr. **Calvin**. Yes; I think that is the best way to go, but that is my opinion.

Mr. **Gore**. We may have a further conversation with you on that.

Dr. **Calvin**. Thank you very much, gentlemen.

Mr. **Gore**. Thank you so much.

Our next two witnesses we are going to ask to appear as a panel, Dr. James E. Hansen with NASA, from the NASA Goddard Space Flight Center and the Institute for Space Studies in New York, and Dr. George Kukla, senior research associate at the Lamont-Doherty Geological Observatory at Palisades, N.Y.

Dr. Hansen and Dr. Kukla, if you would both join us. Without objection, the entire text of your two prepared statements will be inserted in full in the record at the conclusion of your oral presentation.

We will ask you to go first, Dr. Hansen. We all viewed with great interest the NASA results not long ago. Indeed, in the past 6 months, since our last hearing, there has been a dramatic change in the way the scientific community views this, in part because of the work done by the two witnesses on this panel, so please proceed, Dr. Hansen.

STATEMENT OF DR. JAMES E. HANSEN, NASA GODDARD SPACE FLIGHT CENTER AND INSTITUTE FOR SPACE STUDIES

Dr. **Hansen**. Thank you, Mr. Chairman.

My full written testimony is divided into two parts, a report on recent research and my personal recommendations for work that is needed. I would like to summarize both of these parts.

My presentation of the recent research is based on work which we have done at the Goddard Institute for Space Studies in New York, but my recommendations take account of the research by other groups.

With regard to the research findings, I would first like to show you how the global temperature has been changing. I have three Vu-Graphs. Should I wait for that to be set up or should I continue?

Mr. **Gore**. Go ahead and set the screen up. Why don't you proceed with your statement while they are setting it up, or are you going to refer to these Vu-Graphs in the early part of your statement?

Dr. HANSEN. Yes; I am.

Mr. GORE. Well, why don't we withhold a second, then, to get it set up. We apologize to you, Dr. Hansen. We thought the Vu-Graphs were going to be used by DOE, and that is why we didn't have it set up for your presentation.

Dr. HANSEN. Well, I am also a Government employee. [Laughter.]

[Slide shown.]

Dr. HANSEN. Based on temperature records from several hundred stations around the world, we have shown that the global mean temperature shown by the black curve, which is repeated three times, has increased by about four-tenths of a degree, Centigrade, or seven-tenths of a degree, Fahrenheit, during the past 100 years.

As shown by the top red curve, climate models indicate that a warming of that magnitude is expected due to the greenhouse effect of carbon dioxide added to the atmosphere.

But obviously there are other factors which also influence the global temperature. Variations of stratospheric aerosols produced by volcanoes appear to be a primary cause of the variations about the mean trend of increasing temperature. We suspect that there are other important climate-forcing mechanisms, such as changes in the amount of energy coming from the Sun, but we don't have the measurements to reliably define the solar irradiance.

At this time, we can only say that the global temperature is increasing by an amount which is consistent with the growth of atmospheric carbon dioxide, but there are other factors including internal variability of climate system which also affect global temperature.

Now, I would like to also point out a new aspect of the greenhouse effect which is summarized in my next Vu-Graph.

[Slide shown.]

Dr. HANSEN. Recent measurements show that there are several trace atmospheric gases that are now increasing in the atmosphere. These trace gases provide a significant addition to the greenhouse effect of carbon dioxide, as illustrated here for the reported increases in the 1970's.

The growth of these trace gases is a more recent phenomenon than the growth of carbon dioxide. The chlorofluorocarbons, the two on the far right, for example, have been produced in large amounts only during the last 15 to 20 years. The measurements of methane and nitrous oxide are not as accurate as we would like.

But we can conclude that the trace gases are likely to substantially increase the magnitude and accelerate the rate of future climate change. The implication is that we need to consider all of manmade and natural influences on the atmospheric composition if we are to understand how the future climate will change.

Now, I would also like to briefly discuss global sea level, which is illustrated on my next Vu-Graph.

[Slide shown.]

Dr. HANSEN. We have used measurements of sea level from several hundred tide-gage stations located around the world to determine the mean trend of global sea level. We find that the average sea level rose by about 10 centimeters in the past 100 years. About half of that sea level rise can be accounted for by simple thermal expansion of the ocean water.

By inference, the remainder of the sea level rise is probably due to melting of the polar ice sheets. This sea level change is consistent with, and provides some confirmation of, the global warming trend in the past 100 years.

Mr. GORE. Dr. Hansen, this is new evidence, is it not? This has been presented within the last 6 months for the first time, is that correct?

Dr. HANSEN. That is right.

Mr. GORE. Go ahead.

Dr. HANSEN. Mr. Chairman, some scientists have expressed concern that the global warming would cause the West Antarctic ice sheet to disintegrate and melt, raising sea level by perhaps 20 feet. That process will probably require a few centuries. That is the opinion of scientists who have done the most extensive research on the West Antarctic ice sheet.

It is not certain that the carbon dioxide greenhouse warming will be large enough to cause that disintegration. However, it is worth noting that rising sea level itself will tend to enhance the disintegration process, so I believe that study of the West Antarctic ice sheet is one research area that warrants high priority.

Also, I would like to note that a smaller but still significant sea level rise is likely to occur in the coming decades even without collapse of the West Antarctic ice sheet. Just the thermal expansion of ocean water and the slow ice sheet melting, that we have evidence to be occurring, will probably raise sea level between 1 and 2 feet in the next 70 years, if the climate sensitivity is approximately of the magnitude estimated by the National Academy of Sciences committee chaired by Charney.

A sea level rise of 1 to 2 feet is sufficient to cause large-scale beach erosion, intrusion of salt water into low-lying freshwater regions, and a large increase of damaging storm surges in coastal areas. This sea level change is one example of possible climate impact which emphasizes the importance of accurately determining the sensitivity of the climate system to changed atmospheric composition.

Now, I would like to turn to my recommendations for needed research. A great deal of work needs to be done before we can hope to reliably predict future climate, especially regional climate changes, which may be the most important aspect of climate. We can only hope to understand and predict carbon dioxide impacts on climate if we obtain a broad understanding of the climate system.

My choice of high-priority research tasks reflects this need for a broad understanding. In my full written testimony, I discuss in more detail five research tasks which I give the highest priority. Each of these tasks involves measurements but also related research and analysis.

The first task is monitoring the solar irradiance. We must have measurements of the energy which is driving the climate system, measurements of how that energy is changing or not changing, in order to reliably analyze the greenhouse effect.

The second task is monitoring trace gas abundances. We need to know how all of the greenhouse gases are changing. We need to develop a basic understanding of the factors which determine the abundance of these gases.

The third task which I discuss in my written testimony concerns clouds, which are perhaps the greatest source of uncertainty in our attempts to understand climate sensitivity. We need to obtain a good global cloud climatology which will allow us to relate cloud variations to climate variations, in order to build reliable climate models.

The fourth task which I discuss concerns the transport and storage of heat by the oceans, which can greatly affect the timing and the magnitude of manmade climate change. The required measurements in this case are very difficult, and they will not be made quickly.

The fifth task that I discuss, which is the final one, is to improve our understanding of how the ice sheets will respond to global warming, especially the West Antarctic ice sheet. These ice sheet studies will depend upon monitoring the ice sheet topography, which can be done with an altimeter on a satellite.

In summary, Mr. Chairman, I would like to say that it is becoming increasingly clear that we are likely to have substantial climate change during the next several decades if man continues to modify the atmospheric composition at present rates. This conclusion is based in part on the fact that climate models, as they are improved, continue to indicate a large climate impact for increased carbon dioxide and trace gases.

Also, the study of other planetary environments ranging from the thin carbon dioxide atmosphere on Mars to the thick carbon dioxide atmosphere on Venus bear out our basic understanding of the greenhouse effect.

Perhaps most important, the circumstantial evidence contained in observed trends of global temperature, sea level, and sea ice coverage are all consistent with the expectations from the greenhouse theory.

Finally, I would like to emphasize that I believe the carbon dioxide climate effects must be recognized as a component of broader environmental and research issues. In order to identify the carbon dioxide effects on climate and to anticipate man's impact on future climate, it will be necessary to have a strong overall climate research program. This will require contributions from a number of universities and Government agencies.

I thank you for the opportunity to express my opinions.

[The prepared statement, plus attachments, of Dr. Hansen follow:]

GLOBAL CLIMATE CHANGE DUE TO INCREASING ATMOSPHERIC CO_2 AND TRACE GASES

STATEMENT OF:

James E. Hansen
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PRESENTED TO:

Joint Hearing on Carbon Dioxide Research and the Greenhouse Effect

HELD BY:

The United States House of Representatives
Subcommittee on Natural Resources, Agriculture Research and Environment
and the
Subcommittee on Investigations and Oversight
of the
Science and Technology Committee

Dear Mr. Scheuer and Mr. Gore:

You asked me to report on recent research into carbon dioxide and the greenhouse effect. You also asked me to recommend research needed on these and related topics. My testimony is divided accordingly into two parts.

My presentation of recent research is based on work we have done at the Goddard Institute for Space Studies, however, my recommendations take account of research by other groups. Part of our work has been published in the journals Science[1] and Geophysical Research Letters,[2] part is in press at Science[3], and part will be published in papers which are still in preparation. This work was initiated three years ago with funding from the National Aeronautics and Space Administration for FY79-81. It is being continued this year at a reduced level of effort on the basis of NASA support for our climate model development work and funding from the Environmental Protection Agency for applications to CO_2 studies.

My recommendations for research are focused on those areas where I believe improved knowledge will lead to the greatest progress in our understanding of long-range climate and man's impact on climate. These recommendations are my personal opinion of the research which I believe warrants high priority.

RECENT RESEARCH FINDINGS

Global temperature trend. Based on analysis of temperature records from several hundred stations around the world[1], we have shown that global mean temperature increased by 0.2°C between the middle 1960's and 1980 and by 0.4°C between 1880 and 1980. We have also shown[1] that this observed temperature increase is consistent with the calculated greenhouse effect due to measured increases of atmospheric CO_2, although lack of knowledge of other forcing mechanisms and natural climate variability prohibit definitive association of the observed warming with increased CO_2. Variations of stratospheric aerosols produced by volcanoes appear to be the primary cause of observed fluctuations about the mean trend of increasing temperature. As illustrated in Figure 1, CO_2 and stratospheric aerosols can account for most of the variance of global temperature during the past century.

It is expected that other forcings, in addition to CO_2 and aerosols, significantly affect global mean temperature; also natural internal variability of the climate system probably accounts for much of the observed global temperature fluctuations. Unfortunately we do not have the observations needed to specify other suspected climate forcing mechanisms. Even the basic drive for the climate system, the solar radiation incident on the earth, has been measured with sufficient accuracy only for the past 2 years (by the NASA Solar Maximum Mission). The need for measurements of climate forcing mechanisms is the basis for some of the research recommendations given below.

Many other caveats must accompany our analyses of global temperature trends. Such appropriate qualifications are included in our paper[1] published last August in Science.

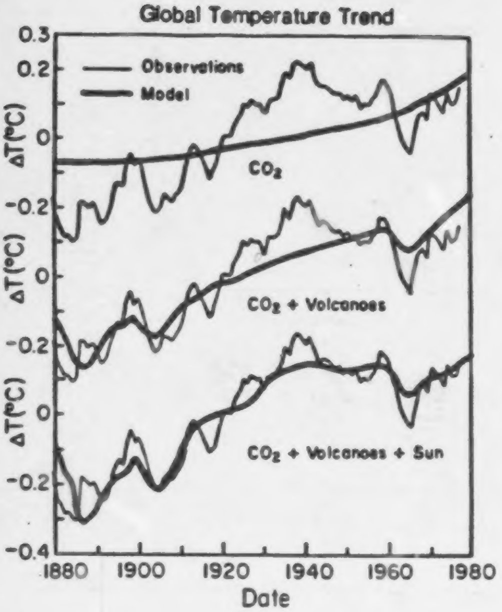

Fig. 1. Observed global temperature trend in past century and climate model results for different forcing mechanisms.[1] The CO_2 and volcano forcings are based on measurements while the solar variability is based on a hypothetical relationship between solar irradiance and visible features on the sun.

Trace gas trends. Increased abundances have been measured recently for several trace atmospheric gases including CH_4, N_2O and the chlorofluorocarbons (CFC's). The growth of these trace gases has not been measured as accurately as it has been for CO_2. However, it is clear that the trace gases have recently been increasing at a rate large enough that they provide a significant addition to the greenhouse effect caused by CO_2. Figure 2 compares the expected greenhouse warmings for the reported increases of CO_2 and trace gases in the 1970's[2]. Although the basic sensitivity of the global climate system to a change of atmospheric composition is still uncertain by at least a factor two, as I will discuss momentarily, the relative effect of trace gases and CO_2 can be computed with greater accuracy.

Substantial growth of these trace gases has probably been a more recent phenomenon than the growth of CO_2. The CFC's, for example, are entirely man-made and they have been produced in large amounts only during the past two decades. The effect of these trace gases can be thought of as reducing the amount of CO_2 required to reach a given level of climate impact: 200 ppm of added CO_2 plus trace gases may be approximately equivalent to 300 ppm of CO_2, the latter figure being a case commonly used for climate model studies. Thus trace gases can be expected to substantially accelerate the rate of future climate change. The implication is that we must consider all man-made and natural influences on atmospheric composition, including all radiatively significant gases, to understand how future climate will change.

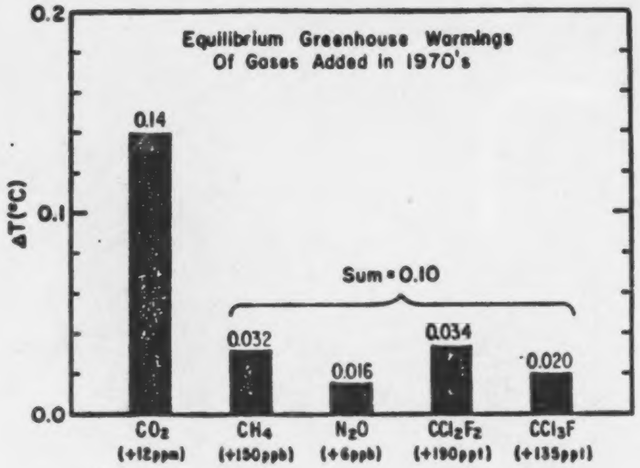

Fig. 2. Greenhouse warmings for estimated 1970-1980 abundance increases of several trace gases, based on a climate model with sensitivity ~3°C for doubled CO_2.

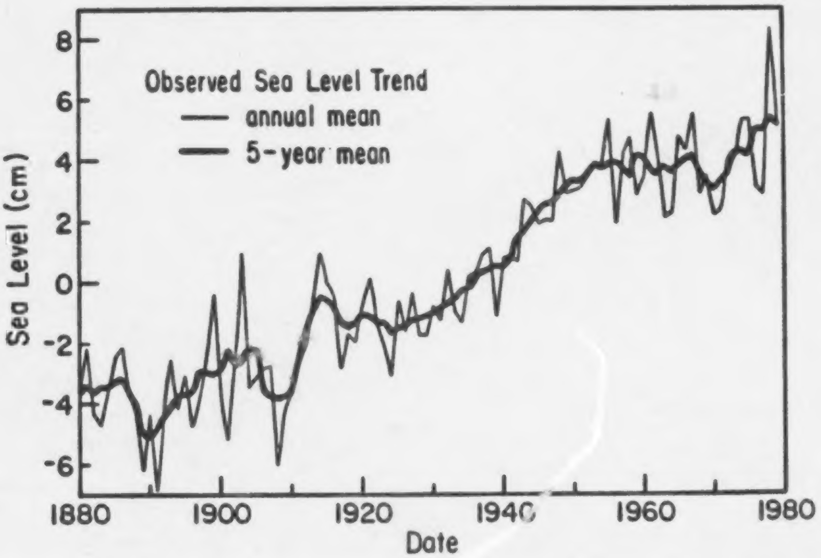

Fig. 3. Global mean sea level trend based on tide gauge measurements[3].

Global sea level trend. Global sea level change is a potentially sensitive indicator of climate change. We have used measurements of sea level from several hundred tide-gauge stations around the world to determine the trend of global sea level[3]. We find that mean sea level rose by about 12 cm in the past century, and by 10 cm after correction is made for long-term vertical movements of the shorelines, as illustrated in Figure 3. This sea level change is highly correlated with the trend of global surface air temperature in the past century. Approximately half of the sea level rise can be accounted for by thermal expansion of the upper layers of the ocean. The remainder of the sea level rise is inferred to be a result of slow net melting of the polar ice sheets.

There are two implication of the rising sea level which I would like to point out. First, the observed sea level change is consistent with and provides some confirmation of the global warming trend which has occurred in the past 100 years. Second, rising sea level may affect the stability of the marine West Antarctic ice sheet. Concern has been expressed[4] that global warming could cause disintegration and melting of this ice sheet to occur relatively rapidly, on the time scale of perhaps a few centuries. Rising sea level will contribute to destabilization of this marine ice sheet, and sea level is now apparently at or near its highest level in the past 100,000 years[3]. I emphasize that we have no evidence that the ice sheet is beginning to disintegrate in a catastrophic fashion. Indeed the sea level change we have found appears to be proportional to the temperature change, and largely a result of thermal expansion of sea water. Nevertheless, since sea level is at a high point and rising, study of the West Antarctic ice sheet warrants close attention.

Significant sea level change is likely to occur in coming decades, even without rapid collapse of the West Antarctic ice sheet. Thermal expansion of sea water will raise sea level 15-30 cm in the next 70 years[3], if the global climate sensitivity is approximately 3°C for doubled CO_2 as estimated by the National Academy of Science committee chaired by Charney[5]. If slow ice sheet melting increases this sea level rise by the same factor as in the past 100 years, a sea level rise of at least 30-60 cm (1-2 feet) would occur by 2050. Although such a sea level rise is modest compared to the 6 m (20 feet) rise which would result from complete removal of the West Antarctic ice sheet, it is sufficient to cause large-scale beach erosion, intrusion of salt water into low-lying fresh water regions and a large increase in damaging storm surges on coastal areas. This projected sea level rise of 1-2 feet is based on physical processes which evidence indicates are occurring.

If atmospheric CO_2 and trace gases continue to increase at current rates, and if present estimates for the resultant greenhouse warming are approximately correct, I believe that we would be prudent to anticipate a sea level rise of at least 30-60 cm (1-2 feet) in the next 70 years.

Global climate sensitivity. There is a large degree of uncertainty in the sensitivity of global climate to change of atmospheric composition. Recent simulations with a three-dimensional global climate model by Dr. Manabe at Princeton University[6] suggest a mean global warming of about 2°C (4°F) for a doubling of atmospheric CO_2, while our studies[7] at the NASA Goddard Institute for Space Studies indicate a mean warming of about 4°C (7°F). The National Academy of Sciences committee[5] estimated that the global mean warming would be 3 ± 1.5°C for a doubling of atmospheric CO_2. This single climate sensitivity number, the mean global warming after the climate system has adjusted to the perturbation, is a critical parameter. It relates to both the cumulative climate change associated with any level of greenhouse gas build-up and to the speed with which climate change will be experienced. Actual transient addition of CO_2 to the atmosphere will constantly be changing climate--understanding how soon the changes will begin to be relatively large compared to past climate fluctuations should be a critical goal of our research.

The range of uncertainty in the climate equilibrium sensitivity to doubled CO_2 covers huge practical differences. The Goddard result suggests that 300 ppm of added CO_2 (or 200 ppm of CO_2 plus moderate trace gas increases), an abundance likely to occur in the coming century, will cause a warming of 4°C globally, and about 10°C in late summer in the vicinity of the West Antarctic ice sheet. The Princeton result suggests that 900 ppm of added CO_2 is required to cause that degree of global warming. Thus it is important to reduce the causes of uncertainty in the models. Note, however, that even the Princeton result represents a large climate change, outside the range of human experience, for doubled CO_2.

A primary cause of the different sensitivities of the climate models is the manner in which they specify or compute the distribution of clouds in the atmosphere. The need to realistically simulate clouds in climate models is the basis for one of the research recommendations which I will provide. There are also many other climate processes which should be simulated more realistically in the climate models. Improvements in representing these processes will require advances in our understanding of atmospheric, oceanic, cryospheric and hydrological processes, advances which are likely to require many years of research.

It would be possible to infer global climate sensitivity from observed climate change in say the past century, if we knew the climate forcings which were acting during that period and the rate of heat penetration into the ocean (assuming that the natural internal noise level in the climate system is sufficiently small). As shown in Figure 1, the observed global temperature trend is in good agreement with a climate sensitivity of 2.8°C for doubled CO_2, if the penetration of heat into the ocean is represented as diffusion beneath the mixed layer with diffusion coefficient $k \sim 1\ cm^2\ sec^{-1}$. This rate of exchange has been widely used by oceanographers as representative of exchange between the mixed layer and deeper ocean. However, our knowledge of ocean circulation and mixing is rudimentary, and the effective exchange coefficient is uncertain by at least a factor of two. Based partly on measured ocean profiles of tritium, which was sprinkled on the ocean surface by atmospheric atomic testing in the 1960's, it has recently been estimated that k may be closer to $2\ cm^2\ sec^{-1}$. This diffusion rate would be consistent with an equilibrium sensitivity of 5°C for doubled CO_2.

Therefore improving our understanding of ocean circulation and mixing processes is very important. If penetration of heat into the thermocline should be represented by an effective diffusion coefficient as large as $2\ cm^2\ sec^{-1}$ this implies that most of the eventual warming due to CO_2 and trace gases already added to the atmosphere has not yet appeared. Thus we may already have "in the pipeline" a great deal more warming than is generally realized. Furthermore, as warming at the surface continues this will tend to stabilize the upper layers of the ocean, which could reduce future exchange with deeper layers. If that occurs, the ocean will be a less effective sink for both heat and atmospheric CO_2 in the future; these positive feedbacks would hasten and enhance the global climate change. These issues underline the importance of obtaining a better understanding of ocean dynamics.

The largest effects of increasing CO_2 and trace gases are likely to be regional climate changes, the shifting of climatic zones. We know for certain that the climate changes will not be globally uniform, but very little is known about how the climate changes will be distributed over the world. Climate models are not yet adequate for accurate absolute projection of regional climate change, but simulations based on current model capabilities could nevertheless provide a great deal of valuable information about possible regional climate effects. Tentative findings from such initial studies should be qualified by all appropriate caveats. These initial studies should be accompanied by concentrated efforts to improve and validate global climate models. As this is done it is important that the climate modeling scientific community receive guidance from business and government about what climate information is most important for the decisions they must make. Only then can the efforts be focused on the most relevant problems.

RECOMMENDED RESEARCH

The global climate system is complex and involves many interacting physical processes. We can only hope to understand and predict CO_2 impacts on climate if we obtain a broad understanding of the climate system. My choice of high priority research tasks reflects this need for a broad understanding.

Solar Monitoring and Analysis. Solar irradiance is the energy which drives terrestrial atmospheric and oceanic motions, and determines the earth's mean temperature and climate. Temporal variations of solar irradiance have long been suspected of being one of the major causes of climate change. Although there may be many different mechanisms causing climate change, in order to sort these factors out it is essential to know the extent to which the basic solar drive of the climate system is changing.

Monitoring of the total solar irradiance and the solar spectral irradiance is now technically possible. The total solar irradiance is being monitored with sufficient accuracy for the first time from the Solar Maximum Mission.

I believe that high priority should be given to establishing a program for continuous monitoring of the total and spectral solar irradiance. Measurement continuity and calibration will be particularly important.

Trace Gas Monitoring. The CO_2 greenhouse effect is only part of a broader environmental issue: man's total impact on atmospheric composition and climate. It is now clear that several trace gases significantly impact the radiation and energy budget at the earth's surface and are capable of modifying our climatic environment. It is thus important that we develop a basic understanding of the factors determining the abundances of such trace gases and their sensitivity to anthropogenic influences.

I believe that highest priority in this area should be given to accurately measuring trace gas trends. It is also important to try to reconstruct past trace gas histories, for example, by measuring trace gas atmospheric absorption profiles in astronomical plates and by measuring the composition of air bubbles trapped in ice sheets.

Clouds. Clouds, and how their properties depend upon climate and climate change, are perhaps the greatest source of uncertainty in our attempts to understand climate sensitivity. Improved ability to model clouds requires as a prerequisite good measurements of global cloud climatology including seasonal and altitude variations of clouds.

The World Climate Research Program (WCRP) has in advanced planning stages an International Satellite Cloud Climatology Project which would extract a 5-year cloud data set from meteorological satellite observations. I believe that this project warrants high priority.

Ocean mixing and heat storage. Horizontal ocean heat transports play a major role in establishing climatic patterns; practicially nothing is known about how these transports will respond to a forced climate change such as CO_2 warming. Storage and vertical penetration of heat in the ocean are a source of great uncertainty in estimates of the timing and magnitude of man-made climate change.

Long-term measurements of heat storage and transport in the ocean are crucial to understanding the CO_2 climate impact. Progress in this area will require substantial time and effort. I believe that it is appropriate for the CO_2 research program to partially support national ocean science efforts in this area, and to give high priority to advancing our understanding of heat storage and transport in the ocean.

Ice sheets. One of the greatest potential effects of CO_2 warming is a large sea level rise, which would occur if the West Antarctic ice sheet were to shrink rapidly. However, there is substantial uncertainty about both the past and future behavior of the West Antarctic ice sheet. In order to make reliable predictions it is necessary to deduce the past behavior of the ice sheet, as well as its present state and the nature of current trends.

Key ice sheet studies depend on monitoring of the ice sheet topography, which will require observations by altimeter from a satellite in polar orbit. It will also be essential to have field work on the ground in selected locations and substantial modeling and theoretical analyses. Because of the importance of the West Antarctic ice sheet to CO_2 climate impact analysis, I believe it is appropriate for the CO_2 research program to partially support ice sheet studies.

SUMMARY

Mr. Chairmen, it is becoming increasingly clear that we should anticipate substantial climate change during the next several decades as a result of man's impact on the composition of the atmosphere. This conclusion is based in part on the fact that climate models, as they are improved and become more realistic, continue to indicate a large climate impact for increased atmospheric CO_2 and trace gases. Also the findings from spacecraft investigations of planetary environments, ranging from the thin CO_2 atmosphere of Mars to the thick CO_2 atmosphere of Venus, bear out our basic understanding of the greenhouse effect. And, perhaps most important, the circumstantial evidence contained in trends of global mean temperature, sea level and sea ice coverage all reveal long range changes which are consistent with expectations from the greenhouse theory.

Mr. Chairmen, I am concerned that CO_2 climate effects be recognized as a component of broader environmental and research issues. In order to identify CO_2 effects on climate and to anticipate man's impact on future climate, it will be necessary to have a strong overall climate research program. The key advances needed to improve our understanding can only be achieved with contributions from a number of universities and government agencies. In order for decision makers to have better information available when it is needed a variety of research efforts must be adequately funded now. I believe that the CO_2 climate research program should supplement those research efforts which have special application to CO_2 climate issues.

Mr. Chairmen, I believe that the research tasks which should be given first priority are those which have long lead times or require continuous measurements; until substantial progress is made on these tasks, we can not fully assess CO_2 climate impact. Among these tasks are measurements of solar irradiance, trace gases, global cloud properties, heat storage and transport by the ocean, and ice sheet properties; these are not the only important measurements, but they are among the more important. I believe that modeling and theoretical studies should also be adequately funded, so that the substantial time required to build and develop competent and effective research teams does not delay progress.

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Reprint Series
28 August 1981, Volume 213, pp. 957–966

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28 August 1981, Volume 213, Number 4511 **SCIENCE**

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Summary. The global temperature rose by 0.2°C between the middle 1960's and 1980, yielding a warming of 0.4°C in the past century. This temperature increase is consistent with the calculated greenhouse effect due to measured increases of atmospheric carbon dioxide. Variations of volcanic aerosols and possibly solar luminosity appear to be primary causes of observed fluctuations about the mean trend of increasing temperature. It is shown that the anthropogenic carbon dioxide warming should emerge from the noise level of natural climate variability by the end of the century, and there is a high probability of warming in the 1980's. Potential effects on climate in the 21st century include the creation of drought-prone regions in North America and central Asia as part of a shifting of climatic zones, erosion of the West Antarctic ice sheet with a consequent worldwide rise in sea level, and opening of the fabled Northwest Passage.

Atmospheric CO_2 increased from 280 to 300 parts per million in 1880 to 335 to 340 ppm in 1980 (*1, 2*), mainly due to burning of fossil fuels. Deforestation and changes in biosphere growth may also have contributed, but their net effect is probably limited in magnitude (*2, 3*). The CO_2 abundance is expected to reach 600 ppm in the next century, even if growth of fossil fuel use is slow (*4*).

Carbon dioxide absorbs in the atmospheric "window" from 7 to 14 micrometers which transmits thermal radiation emitted by the earth's surface and lower atmosphere. Increased atmospheric CO_2 tends to close this window and cause outgoing radiation to emerge from higher, colder levels, thus warming the surface and lower atmosphere by the so-called greenhouse mechanism (*5*). The most sophisticated models suggest a mean warming of 2° to 3.5°C for doubling of the CO_2 concentration from 300 to 600 ppm (*6–8*).

The major difficulty in accepting this theory has been the absence of observed warming coincident with the historic CO_2 increase. In fact, the temperature in the Northern Hemisphere decreased by about 0.5°C between 1940 and 1970 (*9*), a time of rapid CO_2 buildup. In addition, recent claims that climate models overestimate the impact of radiative perturbations by an order of magnitude (*10, 11*) have raised the issue of whether the greenhouse effect is well understood.

We first describe the greenhouse mechanism and use a simple model to compare potential radiative perturbations of climate. We construct the trend of observed global temperature for the past century and compare this with global climate model computations, providing a check on the ability of the model to simulate known climate change. Finally, we compute the CO_2 warming expected in the coming century and discuss its potential implications.

Greenhouse Effect

The effective radiating temperature of the earth, T_e, is determined by the need for infrared emission from the planet to balance absorbed solar radiation:

$$\pi R^2(1 - A)S_0 = 4\pi R^2 \sigma T_e \qquad (1)$$

or

$$T_e = [S_0(1 - A)/4\sigma]^{1/4} \qquad (2)$$

where R is the radius of the earth, A the albedo of the earth, S_0 the flux of solar radiation, and σ the Stefan-Boltzmann constant. For $A \sim 0.3$ and $S_0 = 1367$ watts per square meter, this yields $T_e \sim 255$ K.

The mean surface temperature is $T_s \sim 288$ K. The excess, $T_s - T_e$, is the greenhouse effect of gases and clouds, which cause the mean radiating level to be above the surface. An estimate of the greenhouse warming is

$$T_s \sim T_e + \Gamma H \qquad (3)$$

where H is the flux-weighted mean altitude of the emission to space and Γ is the mean temperature gradient (lapse rate) between the surface and H. The earth's troposphere is sufficiently opaque in the infrared that the purely radiative vertical temperature gradient is convectively unstable, giving rise to atmospheric motions that contribute to vertical transport of heat and result in $\Gamma \sim 5°$ to 6°C per kilometer. The mean lapse rate is less than the dry adiabatic value because of latent heat release by condensation as moist air rises and cools and because the atmospheric motions that transport heat vertically include large-scale atmospheric dynamics as well as local convection. The value of H is ~5 km at midlatitudes (where $\Gamma \sim 6.5°C\ km^{-1}$) and ~6 km in the global mean ($\Gamma \sim 5.5°C\ km^{-1}$).

The surface temperature resulting from the greenhouse effect is analogous to the depth of water in a leaky bucket with constant inflow rate. If the holes in the bucket are reduced slightly in size, the water depth and water pressure will

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increase until the flow rate out of the holes again equals the inflow rate. Analogously, if the atmospheric infrared opacity increases, the temperature of the surface and atmosphere will increase until the emission of radiation from the planet again equals the absorbed solar energy.

The greenhouse theory can be tested by examination of several planets, which provide an ensemble of experiments over a wide range of conditions. The atmospheric composition of Mars, Earth, and Venus lead to mean radiating levels of about 1, 6, and 70 km, and lapse rates of $\Gamma \sim 5°$, $5.5°$, and 7°C km^{-1}, respectively. Observed surface temperatures of these planets confirm the existence and order of magnitude of the predicted greenhouse effect (Eq. 3). Data now being collected by spacecraft at Venus and Mars (*12*) will permit more precise analyses of radiative and dynamical mechanisms that affect greenhouse warming.

One-Dimensional Model

A one-dimensional radiative-convective (1-D RC) model (*5, 13*), which computes temperature as a function of altitude, can simulate planetary temperatures more realistically than the zero-dimensional model of Eq. 1. The sensitivity of surface temperature in 1-D RC models to changes in CO_2 is similar to the sensitivity of mean surface temperature in global three-dimensional models (*6–8*). This agreement does not validate the models; it only suggests that one-dimensional models can simulate the effect of certain basic mechanisms and feedbacks. But the agreement does permit useful studies of global mean temperature change with a simple one-dimensional model.

The 1-D RC model uses a time-marching procedure to compute the vertical temperature profile from the net radiative and convective energy fluxes:

$$T(h, t + \Delta t) = T(h, t) + \frac{\Delta t}{c_p \rho} \left(\frac{dF_r}{dh} + \frac{dF_c}{dh} \right) \qquad (4)$$

where c_p is the heat capacity at constant pressure, ρ the density of air, h the altitude, and dF_r/dh and dF_c/dh the net radiative and convective flux divergences. To compute dF_r/dh the radiative transfer equation is integrated over all frequencies, using the temperature profile of the previous time step and an assumed atmospheric composition. The term dF_c/dh is the energy transport needed to prevent the temperature gradient from exceeding a preassigned limit, usually 6.5°C km^{-1}. This limit parameterizes effects of vertical mixing and large-scale dynamics.

The radiative calculations are made by a method that groups absorption coefficients by strength for efficiency (*14*). Pressure- and temperature-dependent absorption coefficients are from line-by-line calculations for H_2O, CO_2, O_3, N_2O, and CH_4 (*15*), including continuum H_2O absorption (*16*). Climatological cloud cover (50 percent) and aerosol properties (*17*) are used, with appropriate fractions of low (0.3), middle (0.1), and high (0.1) clouds. Wavelength dependences of cloud and aerosol properties are obtained from Mie scattering theory (*14*). Multiple scattering and overlap of gaseous absorption bands are included. Our computations include the weak CO_2 bands at 8 to 12 μm, but the strong 15-μm CO_2 band, which closes one side of the 7- to 20-μm H_2O window, causes ≥ 90 percent of the CO_2 warming.

Model Sensitivity

We examine the main processes known to influence climate model sensitivity by inserting them individually into the model, as summarized in Table 1.

Model 1 has fixed absolute humidity, a fixed lapse rate of 6.5°C km^{-1} in the convective region, fixed cloud altitude, and no snow/ice albedo feedback or vegetation albedo feedback. The increase of equilibrium surface temperature for doubled atmospheric CO_2 is $\Delta T_s \sim 1.2°C$. This case is of special interest because it is the purely radiative-convective result, with no feedback effects.

Model 2 has fixed relative humidity, but is otherwise the same as model 1. The resulting ΔT_s for doubled CO_2 is ~1.9°C. Thus the increasing water vapor with higher temperature provides a feedback factor of ~1.6. Fixed relative humidity is clearly more realistic than fixed absolute humidity, as indicated by physical arguments (*13*) and three-dimensional model results (*7, 8*). Therefore, we use fixed relative humidity in the succeeding experiments and compare models 3 to 6 with model 2.

Model 3 has a moist adiabatic lapse rate in the convective region rather than a fixed lapse rate. This causes the equilibrium surface temperature to be less sensitive to radiative perturbations, and $\Delta T_s \sim 1.4°C$ for doubled CO_2. The reason is that the lapse rate decreases as moisture is added to the air, reducing the temperature difference between the top of the convective region and the ground (ΓH in Eq. 3).

The general circulation of the earth's atmosphere is driven by solar heating of the tropical ocean, and resulting evaporation and vertical transport of energy. The lapse rate is nearly moist adiabatic at low latitudes and should remain so after a climate perturbation. Thus use of a moist adiabatic lapse rate is appropriate for the tropics. But more stable lapse rates at high latitudes make the surface temperature much more sensitive to perturbations of surface heating (*7, 8*), and hence model 3 would underestimate the sensitivity there.

Model 4 has the clouds at fixed temperature levels, and thus they move to a higher altitude as the temperature increases (*18*). This yields $\Delta T_s \sim 2.8°C$ for doubled CO_2, compared to 1.9°C for fixed cloud altitude. The sensitivity increases because the outgoing thermal radiation from cloudy regions is defined by the fixed cloud temperature, requiring greater adjustment by the ground and lower atmosphere for outgoing radiation to balance absorbed solar radiation.

Study of Venus suggests that some clouds occur at a fixed temperature. The Venus cloud tops, which are the primary radiator to space, are at $H \sim 70$ km, where $T \sim T_e$. Analysis of the processes that determine the location of these clouds and the variety of clouds in the belts, zones, and polar regions on Jupiter should be informative. Available evidence suggests that the level of some terrestrial clouds depends on temperature while others occur at a fixed altitude. For example, tropical cirrus clouds moved to a higher altitude in the experiment of Hansen *et al.* (*8*) with doubled CO_2, but low clouds did not noticeably change altitude.

Models 5 and 6 illustrate snow/ice and vegetation albedo feedbacks (*19, 20*). Both feedbacks increase model sensitivity, since increased temperature decreases ground albedo and increases absorption of solar radiation.

Snow, sea ice, and land ice (ice sheets and glaciers) are all included in snow/ice albedo feedback. Snow and sea ice respond rapidly to temperature change, while continental ice sheets require thousands of years to respond. Thus a partial snow/ice albedo feedback is appropriate for time scales of 10 to 100 years. The vegetation albedo feedback was obtained by comparing today's global vegetation patterns with reconstruction of the Wisconsin ice age (*20*). Uncertainties in the reconstruction, the time scale of vegetation response, and man's potential impact on vegetation prevent reliable assessment of this feedback, but its estimated magnitude emphasizes the need to monitor global vegetation and surface albedo.

Model 4 has our estimate of appropriate model sensitivity. The fixed 6.5°C km^{-1} lapse rate is a compromise between expected lower sensitivity at low latitudes and greater sensitivity at high latitudes. Both cloud temperature and snow/ice albedo feedback should be partly effective, so for simplicity one is included.

The sensitivity of the climate model we use is thus $\Delta T_s \sim 2.8°C$ for doubled CO_2, similar to the sensitivity of three-dimensional climate models (*6–8*). The estimated uncertainty is a factor of 2. This sensitivity (i) refers to perturbations about today's climate and (ii) does not include feedback mechanisms effective only on long time scales, such as changes of ice sheets or ocean chemistry.

Table 1. Equilibrium surface temperature increase due to doubled CO_2 (from 300 to 600 ppm) in 1-D RC models. Model 1 has no feedbacks affecting the atmosphere's radiative properties. Feedback factor f specifies the effect of each added process on model sensitivity to doubled CO_2; F is the equilibrium thermal flux into the ground if T_s is held fixed (infinite heat capacity) when CO_2 is doubled. Abbreviations: FRH, fixed relative humidity; FAH, fixed absolute humidity; 6.5LR, 6.5°C km^{-1} limiting lapse rate; MALR, moist adiabatic limiting lapse rate; FCA, fixed cloud altitude, FCT, fixed cloud temperature; SAF, snow/ice albedo feedback; and VAF, vegetation albedo feedback. Models 5 and 6 are based on f values from Wang and Stone (*19*) and Cess (*20*), respectively, and ΔT_s of model 2.

Model	Description	ΔT_s (°C)	f	F ($W\ m^{-2}$)
1	FAH, 6.5LR, FCA	1.22	1	4.0
2	FRH, 6.5LR, FCA	1.94	1.6	3.9
3	Same as 2, except MALR replaces 6.5LR	1.37	0.7	4.0
4	Same as 2, except FCT replaces FCA	2.78	1.4	3.9
5	Same as 2, except SAF included	2.5–2.8	1.3–1.4	
6	Same as 2, except VAF included	~3.5	~1.8	

Model Time Dependence

The time dependence of the earth's surface temperature depends on the heat capacity of the climate system. Heat capacity of land areas can be neglected, since ground is a good insulator. However, the upper 100 m of the ocean is rapidly mixed, so its heat capacity must be accounted for. The ocean beneath the mixed layer may also affect surface temperature, if the thermal response time of the mixed layer is comparable to the time for exchange of heat with deeper layers.

The great heat capacity of the ocean and ready exchange of continental and marine air imply that the global climate response to perturbations is determined by the response of the ocean areas. However, this response is affected by horizontal atmospheric heat fluxes from and to the continents. Ready exchange of energy between the ocean surface and atmosphere "fixes" the air temperature, and the ocean in effect removes from the atmosphere any net heat obtained from the continents. Thus the horizontal flux due to a climate perturbation's heating (or cooling) of the continents adds to the vertical heat flux into (or out of) the ocean surface. The net flux into the ocean surface is therefore larger than it would be for a 100 percent ocean-covered planet by the ratio of global area to ocean area, totaling ~5.7 $W\ m^{-2}$ for doubled CO_2 rather than ~4 $W\ m^{-2}$. In a climate model that employs only a mixed-layer ocean, it is equivalent to use the flux ~4 $W\ m^{-2}$ with the area-weighted mean land-ocean heat capacity.

The thermal response time of the ocean mixed layer would be ~3 years if it were not for feedback effects in the climate system. For example, assume that the solar flux absorbed by a planet changes suddenly from $F_0 = \sigma T_0^4$ to $F_1 = F_0 + \Delta F = \sigma T_1^4$, with $\Delta F << F_0$. The rate of change of heat in the climate system is

$$d(cT)/dt = \sigma T_1^4 - \sigma T^4 \qquad (5)$$

where c is heat capacity per unit area. Since $T_1 - T_0 << T_0$, the solution is

$$T - T_1 = (T_0 - T_1)e^{-t/t_{\text{thr}}} \qquad (6)$$

where

$$t_{\text{thr}} = c/4\sigma T_1^3 \qquad (7)$$

Thus the planet approaches a new equilibrium temperature exponentially with e-folding time t_{thr}. If the heat capacity is provided by 70 m of water (100 m for ocean areas) and the effective temperature is 255 K, t_{thr} is 2.8 years.

This estimate does not account for climate feedback effects, which can be analyzed with the 1-D RC model. Table 1 shows that the initial rate of heat storage in the ocean is independent of feedbacks. Thus the time needed to reach equilibrium for model 4 is larger by the factor ~2.8°C/1.2°C than for model 1, which excludes feedbacks. The e-folding time for adjustment of mixed-layer temperature is therefore ~6 years for our best estimate of model sensitivity to doubled CO_2. This increase in thermal response time is readily understandable, because feedbacks come into play only gradually after some warming occurs.

It would take ~50 years to warm up the thermocline and mixed layer if they were rapidly mixed, or 250 years for the entire ocean. Turnover of the deep ocean, driven by formation of cold bottom water in the North Atlantic and Antarctic oceans with slow upwelling at low latitudes, is thought to require 500 to 1000 years (*21*), suggesting that the deep ocean does not greatly influence surface temperature sensitivity. However, there may be sufficient heat exchange between the mixed layer and thermocline to delay full impact of a climate perturbation by a few decades (*6, 22, 23*). The primary mechanism of exchange is nearly horizontal movement of water along surfaces of constant density (*21*).

Delay of CO_2 warming by the ocean can be illustrated with a "box diffusion" model (*24*), in which heat is stirred instantly through the mixed layer and diffused into the thermocline with diffusion coefficient k. Observed oceanic penetration by inert chemical tracers suggests that k is of order 1 square centimeter per second (*2, 3, 24*).

The warming calculated with the one-dimensional model for the CO_2 increase from 1880 to 1980 (*25*) is 0.5°C if ocean heat capacity is neglected (Fig. 1). The heat capacity of just the mixed layer reduces this to 0.4°C, a direct effect of the mixed layer's 6-year thermal response time. Diffusion into the thermocline further reduces the warming to 0.25°C for $k = 1\ cm^2\ sec^{-1}$, an indirect effect of the mixed layer's 6-year e-folding time, which permits substantial exchange with the thermocline.

The mixed-layer model and thermocline model bracket the likely CO_2 warming. The thermocline model is preferable for small climate perturbations that do not affect ocean mixing. However, one effect of warming the ocean surface will be increased vertical stability, which could reduce ocean warming and make the surface temperature response more like that of the mixed-layer case.

Lack of knowledge of ocean processes

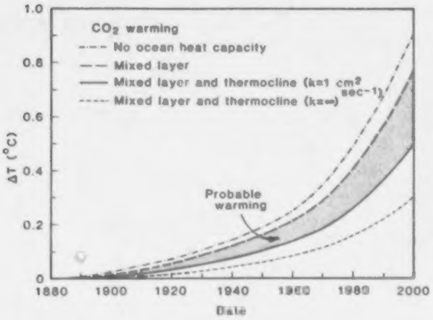


Fig. 1. Dependence of CO_2 warming on ocean heat capacity. Heat is rapidly mixed in the upper 100 m of the ocean and diffused to 1000 m with diffusion coefficient *k*. The CO_2 abundance, from (*25*), is 293 ppm in 1880, 335 ppm in 1980, and 373 ppm in 2000. Climate model equilibrium sensitivity is 2.8°C for doubled CO_2.

primarily introduces uncertainties about the time dependence of the global CO_2 warming. The full impact of the warming may be delayed several decades, but since man-made increases in atmospheric CO_2 are expected to persist for centuries (*1*, *2*, *6*), the warming will eventually occur.

Radiative Climate Perturbations

Identification of the CO_2 warming in observed climate depends on the magnitude of climate variability due to other factors. Most suspected causes of global climate change are radiative perturbations, which can be compared to identify those capable of counteracting or reinforcing the CO_2 warming.

A 1 percent increase of solar luminosity would warm the earth 1.6°C at equilibrium (Fig. 2) on the basis of model 4, which we employ for all radiative perturbations to provide a uniform comparison. Since the effect is linear for small changes of solar luminosity, a change of 0.3 percent would modify the equilibrium global mean temperature by 0.5°C, which is as large as the equilibrium warming for the cumulative increase of atmospheric CO_2 from 1880 to 1980. Solar luminosity variations of a few tenths of 1 percent could not be reliably measured with the techniques available during the past century, and thus are a possible cause of part of the climate variability in that period.

Atmospheric aerosol effects depend on aerosol composition, size, altitude, and global distribution (*26*). Based on model calculations, stratospheric aerosols that persist for 1 to 3 years after large volcanic eruptions can cause substantial cooling of surface air (Fig. 2). The cooling depends on the assumption that the particles do not exceed a few tenths of a micrometer in size, so they do not cause greenhouse warming by blocking terrestrial radiation, but this condition is probably ensured by rapid gravitational settling of larger particles. Temporal variability of stratospheric aerosols due to volcanic eruptions appears to have been responsible for a large part of the observed climate change during the past century (*27–30*), as shown below.

The impact of tropospheric aerosols on climate is uncertain in sense and magnitude due to their range of composition, including absorbing material such as carbon and high-albedo material such as sulfuric acid, and their heterogeneous spatial distribution. Although man-made tropospheric aerosols are obvious near their source, aerosol opacity does not appear to have increased much in remote regions (*31*). Since the climate impact of anthropogenic aerosols is also reduced by the opposing effects of absorbing and high-albedo materials, it is possible that they have not had a primary effect on global temperature. However, global monitoring of aerosol properties is needed for conclusive analysis.

Ground albedo alterations associated with changing patterns of vegetation coverage have been suggested as a cause of global climate variations on time scales of decades to centuries (*32*). A global surface albedo change of 0.015, equivalent to a change of 0.05 over land areas, would affect global temperature by 1.3°C. Since this is a 25 percent change in mean continental ground albedo, it seems unlikely that ground albedo variations have been the primary cause of recent global temperature trends. However, global monitoring of ground albedo is needed to permit definitive assessment of its role in climate variability.

High and low clouds have opposite effects on surface temperature (Fig. 2), high clouds having a greenhouse effect while low clouds cool the surface (*14*, *33*). However, the nature and causes of variability of cloud cover, optical thickness, and altitude distribution are not well known, nor is it known how to model reliably cloud feedbacks that may occur in response to climate perturbations. Progress may be made after accurate cloud climatology is obtained from global observations, including seasonal and interannual cloud variations. In the

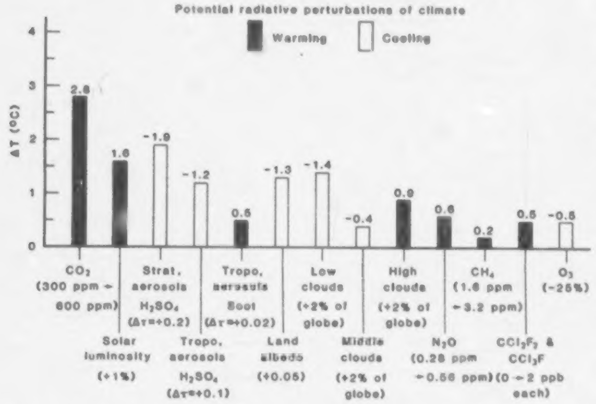


Fig. 2. Surface temperature effect of various global radiative perturbations, based on the 1-D RC model 4 (Table 1). Aerosols have the physical properties specified by (*17*). Dependence of ΔT on aerosol size, composition, altitude, and optical thickness is illustrated by (*26*). The $\Delta\tau$ for stratospheric aerosols is representative of a very large volcanic eruption.

meantime, some limits are implicitly placed on global cloud feedback by empirical tests of the climate system's sensitivity to radiative perturbations, as discussed below.

Trace gases that absorb in the infrared can warm the earth if their abundance increases (*5, 34*). The abundance of chlorofluorocarbons (Freons) increased from a negligible amount a few decades ago to 0.3 part per billion for CCl_2F_2 and 0.2 ppb for CCl_3F (*35*), with an equilibrium greenhouse warming of ~ 0.06°C. Recent measurement of a 0.2 percent per year increase of N_2O suggests a cumulative increase to date of 17 ppb (*36*), with an equilibrium warming of ~ 0.03°C. Tentative indications of a 2 percent per year increase in CH_4 imply an equilibrium warming < 0.1°C for the CH_4 increase to date (*37*). No major trend of O_3 abundance has been observed, although it has been argued that continued increase of Freons will reduce O_3 amounts (*38*). The net impact of measured trace gases has thus been an equilibrium warming of 0.1°C or slightly larger. This does not greatly alter analyses of temperature change over the past century, but trace gases will significantly enhance future greenhouse warming if recent growth rates are maintained.

We conclude that study of global climate change on time scales of decades and centuries must consider variability of stratospheric aerosols and solar luminosity, in addition to CO_2 and trace gases. Tropospheric aerosols and ground albedo are potentially significant, but require better observations. Cloud variability will continue to cause uncertainty until accurate monitoring of global cloud properties provides a basis for realistic modeling of cloud feedback effects; however, global feedback is implicitly checked by comparison of climate model sensitivity to empirical climate variations, as done below.

Observed Temperature Trends

Data archives (*39*) contain surface air temperatures of several hundred stations for the last century. Problems in obtaining a global temperature history are due to the uneven station distribution (*40*), with the Southern Hemisphere and ocean areas poorly represented, and the smaller number of stations for earlier times.

We combined these temperature records with a method designed to extract mean temperature trends. The globe was divided by grids with a spacing not larger than the correlation distance for primary dynamical transports (*41*), but large enough that most boxes contained one or more stations. The results shown were obtained with 40 equal-area boxes in each hemisphere, but the conclusions are not sensitive to the exact spacing. Temperature trends for stations within a box were combined successively:

$$T_{1,n}(t) = \frac{(n^* - 1)T_{1,n} + T_n - \bar{T}_n + \bar{T}_{1,n}}{n^*} \qquad (8)$$

to obtain a single trend for each box, where the bar indicates a mean for the years in which there are records for both T_n and the cumulative $T_{1,n}$ and $n^*(t)$ is the number of stations in $T_{1,n}(t)$. Trends for boxes in a latitude zone were combined with each box weighted equally, and the global trend was obtained by area-weighting the trends for all latitude zones. A meaningful result begins in the 1880's, since thereafter continuous records exist for at least two widely separated longitudes in seven of the eight latitude zones (continuous Antarctic temperatures begin in the 1950's). Results are least reliable for 1880 to 1900; by 1900, continuous records exist for more than half of the 80 boxes.

The temperature trends in Fig. 3 are smoothed with a 5-year running mean to make the trends readily visible. Part of the noise in the unsmoothed data results from unpredictable weather fluctuations, which affect even 1-year means (*42*). None of our conclusions depends on the nature of the smoothing.

Northern latitudes warmed ~ 0.8°C between the 1880's and 1940, then cooled ~ 0.5°C between 1940 and 1970, in agreement with other analyses (*9, 43*). Low latitudes warmed ~ 0.3°C between 1880 and 1930, with little change thereafter. Southern latitudes warmed ~ 0.4°C in the past century; results agree with a prior analysis for the late 1950's to middle 1970's (*44*). The global mean temperature increased ~ 0.5°C between 1885 and 1940, with slight cooling thereafter.

A remarkable conclusion from Fig. 3 is that the global temperature is almost as high today as it was in 1940. The common misconception that the world is cooling is based on Northern Hemisphere experience to 1970.

Another conclusion is that global surface air temperature rose ~ 0.4°C in the past century, roughly consistent with calculated CO_2 warming. The time history of the warming obviously does not follow the course of the CO_2 increase (Fig. 1), indicating that other factors must affect global mean temperature.

Model Verification

Natural radiative perturbations of the earth's climate, such as those due to aerosols produced by large volcanic

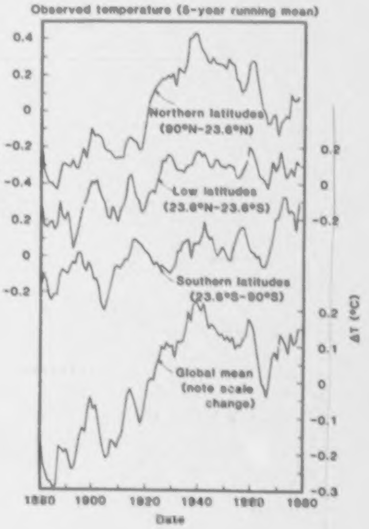
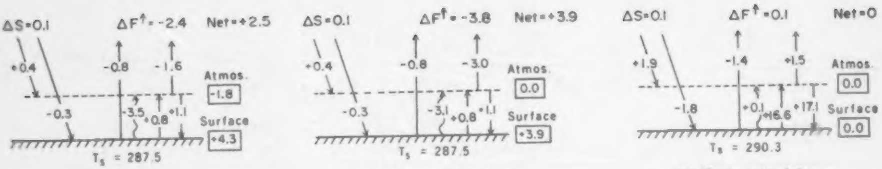


Fig. 3. Observed surface air temperature trends for three latitude bands and the entire globe. Temperature scales for low latitudes and global mean are on the right.



(a) Immediate response

(b) A few months later

(c) Many years later

Fig. 4. Change of fluxes (watts per square meter) in the 1-D RC model when atmospheric CO_2 is doubled (from 300 to 600 ppm). Symbols: ΔS, change in solar radiation absorbed by the atmosphere and surface; $\Delta F \uparrow$, change in outward thermal radiation at top of the atmosphere. The wavy line represents convective flux; other fluxes are radiative.

eruptions, permit a valuable test of model sensitivity. Previous study of the best-documented large volcanic eruption, Mount Agung in 1963, showed that tropical tropospheric and stratospheric temperature changes computed with a one-dimensional climate model were of the same sign and order of magnitude as observed changes (*45*). It was assumed that horizontal heat exchange with higher latitudes was not altered by the radiative perturbation.

We reexamined the Mount Agung case for comparison with the present global temperature record, using our model with sensitivity ~ 2.8°C. The model, with a maximum global mean aerosol increase in the optical depth $\Delta\tau = 0.12$ (*45*), yields a maximum global cooling of 0.2°C when only the mixed-layer heat capacity is included and 0.1°C when heat exchange with the deeper ocean is included with $k = 1$ cm^2 sec^{-1}. Observations suggest a cooling of this magnitude with the expected time lag of 1 to 2 years. Noise or unexplained variability in the observations prevents more definitive conclusions, but similar cooling is indicated by statistical studies of temperature trends following other large volcanic eruptions (*46*).

A primary lesson from the Mount Agung test is the damping of temperature change by the mixed layer's heat capacity, without which the cooling would have exceeded 1.1°C (Fig. 2). The effect can be understood from the time constant of the perturbation and thermal response time of the mixed layer: $\Delta T \sim \{1 - \exp[(-1 \text{ year})/(6 \text{ years})]\} \times 1.1°\text{C} \sim 0.17°\text{C}$, for the case $k = 0$. This large reduction of the climate response occurs for a perturbation that (unlike CO_2) is present for a time shorter than the thermal response time of the ocean surface.

Phenomena that alter the regional radiation balance provide another model test. Idso (*11*) found a consistent "empirical response function" for several such phenomena, which was 0.17°C per watt per square meter in midcontinent and was half as large on the coast. This response must depend on the rate of mixing of marine and continental air, since the phenomena occur on time scales less than the thermal relaxation time of the ocean surface. Thus, as one test of horizontal atmospheric transports, we read from our three-dimensional climate model (*8*) the quantities (solar insolation and temperature) that form Idso's empirical response function for seasonal change of insolation. Results ranged from 0.2°C W^{-1} m^2 in midcontinent, and about half that on the coast, to a value an order of magnitude smaller over the ocean, in agreement with the empirical response (*11*).

To relate these empirical tests to the CO_2 greenhouse effect, we illustrate the flux changes in the 1-D RC model when CO_2 is doubled. For simplicity we consider an instantaneous doubling of CO_2, and hence the time dependence of the response does not represent the transient response to a steady change in CO_2. The immediate response to the doubling includes (Fig. 4a): (i) reduced emission to space (− 2.4 W m^{-2}), because added CO_2 absorption raises the mean altitude of emission to a higher, colder level; (ii) increased flux from atmosphere to ground (+ 1.1 W m^{-2}); and (iii) increased stratospheric cooling but decreased tropospheric cooling. The radiative warming of the troposphere decreases the "convective" flux (latent and sensible heat) from the ground by 3.5 W m^{-2} as a consequence of the requirement to conserve energy. There is a small increase in absorption of near-infrared radiation, the atmosphere gaining energy (+ 0.4 W m^{-2}) and the ground losing energy (− 0.3 W m^{-2}). The net effect is thus an energy gain for the planet (+ 2.5 W m^{-2}) with heating of the ground (+ 4.3 W m^{-2}) and cooling of the (upper) atmosphere (− 1.8 W m^{-2}). These flux changes are independent of feedbacks and are not sensitive to the critical lapse rate.

A few months after the CO_2 doubling (Fig. 4b) the stratospheric temperature has cooled by ~ 5°C. Neither the ocean nor the troposphere, which is convectively coupled to the surface, have responded yet. The planet radiates 3.8 W m^{-2} less energy to space than in the comparison case with 300 ppm CO_2, because of the cooler stratosphere and greater altitude of emission from the troposphere. The energy gained by the earth at this time is being used to warm the ocean.

Years later (Fig. 4c) the surface temperature has increased 2.8°C. Almost half the increase (1.2°C) is the direct CO_2 greenhouse effect. The remainder is due to feedbacks, of which 1.0°C is the well-established H_2O greenhouse effect.

The greenhouse process represented in Fig. 4 is simply the "leaky bucket" phenomenon. The increased infrared opacity causes an immediate decrease of thermal radiation from the planet, thus forcing the temperature to rise until energy balance is restored. Temporal variations of the fluxes and temperatures are due to the response times of the atmosphere and surface.

Surface warming of ~ 3°C for doubled CO_2 is the status after energy balance has been restored. This contrasts with the Agung case and the cases considered by Idso (*11*), which are all nonequilibrium situations.

The test of the greenhouse theory provided by the extremes of equilibrium climates on the planets and short-term radiative perturbations is reassuring, but inadequate. A crucial intermediate test is climate change on time scales from a few years to a century.

Model versus Observations for the Past Century

Simulations of global temperature change should begin with the known forcings: variations of CO_2 and volcanic aerosols. Solar luminosity variations, which constitute another likely mechanism, are unknown, but there are hypotheses consistent with observational constraints that variations not exceed a few tenths of 1 percent.

We developed an empirical equation that fits the heat flux into the earth's surface calculated with the 1-D RC climate model (model 4):

$$F(t) = 0.018\Delta p/(1 + 0.0022\Delta p)^{0.6} - 17\Delta\tau - 1.5(\Delta\tau)^2 + 220\Delta S/S_0 - 1.5\Delta T + 0.033\,(\Delta T)^2 - 1.04 \times 10^{-4}\Delta p\Delta T + 0.29\Delta T\Delta\tau \quad (9)$$

where $F(t)$ is in watts per square meter, p is the amount of CO_2 in parts per million above an "equilibrium" value (293 ppm), ΔS is the difference between solar luminosity and an equilibrium value S_0, $\Delta\tau$ is the optical depth of stratospheric aerosols above a background amount, and ΔT is the difference between current surface temperature and the equilibrium value for $\Delta p = \Delta S = \Delta\tau = 0$. Equation 9 fits the one-dimensional model results to better than 1 percent for $0 \leq \Delta p \leq 1200$ ppm, $0.98 \leq \Delta S/S_0 \leq 1.02$, and $\Delta\tau \leq 0.5$. For the mixed-layer ocean model $T_s(t)$ follows from $dT_s/dt = F(t)/c_0$, where c_0 is the heat capacity of the ocean mixed layer per unit area. If the true mixed-layer depth is used to obtain c_0, $F(t)$ must be multiplied by 1/0.7, the ratio of global area to ocean area. Diffusion of heat into the deeper ocean can then also be included by means of the diffusion equation with T_s as its upper boundary condition.

The CO_2 abundance increased from 293 ppm in 1880 to 335 ppm in 1980 (*25*), based on recent accurate observations, earlier less accurate observations, and carbon cycle modeling. The error for 1880 probably does not exceed 10 ppm (*1, 2*).

Volcanic aerosol radiative forcing can be obtained from Lamb's (*27*) dust veil index (DVI), which is based mainly on atmospheric transmission measurements after 1880. We convert DVI to optical depth by taking Mount Agung (DVI = 800) to have the maximum $\Delta\tau = 0.12$. The aerosol optical depth histories of Mitchell (*47*) and Pollack *et al.* (*29*), the latter based solely on transmission measurements, are similar to Lamb's. We use aerosol microphysical properties from (*45*). The error in volcanic aerosol radiative forcing probably does not exceed a factor of 2.

Solar variability is highly conjectural, so we first study CO_2 and volcanic aerosol forcings and then add solar variations. We examine the hypothesis of Hoyt (*48*) that the ratio, r, of umbra to penumbra areas in sunspots is proportional to solar luminosity: $\Delta S/S_0 = f(r - r_0)$. Hoyt's rationale is that the penumbra, with a weaker magnetic field than the umbra, is destroyed more readily by an increase of convective flux from below. We take $f = 0.03$, which implies a peak-to-peak amplitude of ~ 0.4 percent for $\Delta S/S_0$ in the past century, or an amplitude of ~ 0.2 percent for the mean trend line. Taking S_0 as the mean for 1880 to 1976 yields $r_0 = 0.2$. The resulting $\Delta S/S_0$ has no observational corroboration, but serves as an example of solar variability of a plausible magnitude.

Radiative forcing by CO_2 plus volcanoes and forcing by CO_2 plus volcanoes plus the sun both yield a temperature trend with a strong similarity to the observed trend of the past century (Fig. 5), which we quantify below. If only the heat capacity of the mixed layer is included, the amplitude of the computed temperature variations is larger than observed. However, mixing of heat into the deeper ocean with $k = 1$ cm^2 sec^{-1} brings both calculated trends into rough agreement with observations.

The main uncertainties in the climate model—that is, its "tuning knobs"—are (i) the equilibrium sensitivity and (ii) the rate of heat exchange with the ocean beneath the mixed layer. The general correlation of radiative forcings with global temperatures suggests that model uncertainties be constrained by requiring agreement with the observed temperature trend.

Therefore, we examined a range of model sensitivities, choosing a diffusion coefficient for each to minimize the residual variance between computed and observed temperature trends. Equilibrium sensitivities of 1.4°, 2.8°, and 5.6°C required $k = 0$, 1.2, and 2.2 cm^2 sec^{-1}, respectively. All models with sensitivities of 1.4° to 5.6°C provide a good fit to the observations. The smallest acceptable sensitivity is ~ 1.4°C, because it requires zero heat exchange with the deeper ocean. Sensitivities much higher than 5.6°C would require greater heat exchange with the deep ocean than is believed to be realistic (*21, 22*).

Radiative forcing by CO_2 plus volcanoes accounts for 75 percent of the variance in the 5-year smoothed global temperature, with correlation coefficient 0.9. The hypothesized solar luminosity variation (*48*) improves the fit, as a consequence of the luminosity peaking in the 1930's and declining into the 1970's, leaving a residual variance of only 10 percent. The improved fit provided by Hoyt's solar variability represents a posteriori selection, since other hypothesized solar variations that we examined [for instance (*49*)] degrade the fit. This

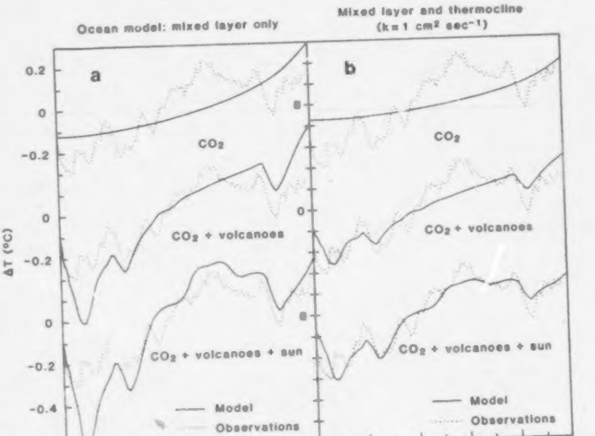


Fig. 5. Global temperature trend obtained from climate model with sensitivity 2.8°C for doubled CO_2. The results in (a) are based on a 100-m mixed-layer ocean for heat capacity; those in (b) include diffusion of heat into the thermocline to 1000 m. The forcings by CO_2, volcanoes, and the sun are based on Broecker (*25*), Lamb (*27*), and Hoyt (*48*). Mean ΔT is zero for observations and model.

Table 2. Energy supplied and CO_2 released by fuels.

Fuel	Energy supplied in 1980*		CO_2 release per unit energy (oil = 1)	Airborne CO_2 added in 1980*		CO_2 added through 1980 (ppm)	Potential airborne CO_2 in virgin reservoirs† (ppm)
	(10^{19} J)	(%)		(%)	(ppm)		
Oil	12	40	1	50	0.7	11	70
Coal	7	24	5/4	35	0.5	26	1000
Gas	5	16	3/4	15	0.2	5	50
Oil shale, tar sands, heavy oil	0	0	7/4	0	0	0	100
Nuclear, solar, wood, hydroelectric	6	20	0	0	0	0	0
Total	30	100		100	1.4	42	1220

*Based on late 1970's. †Reservoir estimates assume that half the coal above 3000 feet can be recovered and that oil recovery rates will increase from 25 to 30 percent to 40 percent. Estimate for unconventional fossil fuels may be low if techniques are developed for economic extraction of "synthetic oil" from deposits that are deep or of marginal energy content. It is assumed that the airborne fraction of released CO_2 is fixed.

evidence is too weak to support any specific solar variability.

The general agreement between modeled and observed temperature trends strongly suggests that CO_2 and volcanic aerosols are responsible for much of the global temperature variation in the past century. Key consequences are: (i) empirical evidence that much of the global climate variability on time scales of decades to centuries is deterministic and (ii) improved confidence in the ability of models to predict future CO_2 climate effects.

Projections into the 21st Century

Prediction of the climate effect of CO_2 requires projections of the amount of atmospheric CO_2, which we specify by (i) the energy growth rate and (ii) the fossil fuel proportion of energy use. We neglect other possible variables, such as changes in the amount of biomass or the fraction of released CO_2 taken up by the ocean.

Energy growth has been 4 to 5 percent per year in the past century, but increasing costs will constrain future growth (*1*, *4*). Thus we consider fast growth (~ 3 percent per year, specifically 4 percent per year in 1980 to 2020, 3 percent per year in 2020 to 2060, and 2 percent per year in 2060 to 2100), slow growth (half of fast growth), and no growth as representative energy growth rates.

Fossil fuel use will be limited by available resources (Table 2). Full use of oil and gas will increase CO_2 abundance by < 50 percent of the preindustrial amount. Oil and gas depletion are near the 25 percent level, at which use of a resource normally begins to be limited by supply and demand forces (*4*). But coal, only 2 to 3 percent depleted, will not be so constrained for several decades.

The key fuel choice is between coal and alternatives that do not increase atmospheric CO_2. We examine a synfuel option in which coal-derived synthetic fuels replace oil and gas as the latter are depleted, and a nuclear/renewable resources option in which the replacement fuels do not increase CO_2. We also examine a coal phaseout scenario: after a specific date coal and synfuel use are held constant for 20 years and then phased out linearly over 20 years.

Projected global warming for fast growth is 3° to 4.5°C at the end of the next century, depending on the proportion of depleted oil and gas replaced by synfuels (Fig. 6). Slow growth, with depleted oil and gas replaced equally by synfuels and nonfossil fuels, reduces the warming to ~ 2.5°C. The warming is only slightly more than 1°C for either (i) no energy growth, with depleted oil and gas replaced by nonfossil fuels, or (ii) slow energy growth, with coal and synfuels phased out beginning in 2000.

Other climate forcings may counteract or reinforce CO_2 warming. A decrease of solar luminosity from 1980 to 2100 by 0.6 percent per century, large compared to measured variations, would decrease the warming ~ 0.7°C. Thus CO_2 growth as large as in the slow-growth scenario would overwhelm the effect of likely solar variability. The same is true of other radiative perturbations; for instance, volcanic aerosols may slow the rise in temperature, but even an optical thickness of 0.1 maintained for 120 years would reduce the warming by less than 1.0°C.

When should the CO_2 warming rise out of the noise level of natural climate variability? An estimate can be obtained by comparing the predicted warming to the standard deviation, σ, of the observed global temperature trend of the past century (*50*). The standard deviation, which increases from 0.1°C for 10-year intervals to 0.2°C for the full century, is the total variability of global temperature; it thus includes variations due to any known radiative forcing, other variations of the true global temperature due to unidentified causes, and noise due to imperfect measurement of the global temperature. Thus if T_0 is the current 5-year smoothed global temperature, the 5-year smoothed global temperature in 10 years should be in the range $T_0 \pm 0.1$°C with probability ~ 70 percent, judging only from variability in the past century.

The predicted CO_2 warming rises out of the 1σ noise level in the 1980's and the 2σ level in the 1990's (Fig. 7). This is independent of the climate model's equilibrium sensitivity for the range of likely values, 1.4° to 5.6°C. Furthermore, it does not depend on the scenario for atmospheric CO_2 growth, because the amounts of CO_2 do not differ substantially until after year 2000. Volcanic eruptions of the size of Krakatoa or Agung may slow the warming, but barring an unusual coincidence of eruptions, the delay will not exceed several years.

Nominal confidence in the CO_2 theory will reach ~ 85 percent when the temperature rises through the 1σ level and ~ 98 percent when it exceeds 2σ. However, a portion of σ may be accounted for in the future from accurate knowledge of some radiative forcings and more precise knowledge of global temperature. We conclude that CO_2 warming should rise above the noise level of natural climate variability in this century.

Potential Consequences of Global Warming

Practical implications of CO_2 warming can only be crudely estimated, based on climate models and study of past climate. Models do not yet accurately simulate many parts of the climate system, especially the ocean, clouds, polar sea ice, and ice sheets. Evidence from past climate is also limited, since the few recent warm periods were not as extreme as the warming projected to accompany full use of fossil fuels, and the climate forcings and rate of climate change may have been different. However, if checked against our understanding of the physical processes and used with caution, the models and data on past climate provide useful indications of possible future climate effects (*51*).

Paleoclimatic evidence suggests that surface warming at high latitudes will be two to five times the global mean warming (*52*–*55*). Climate models predict the larger sensitivity at high latitudes and trace it to snow/ice albedo feedback and greater atmospheric stability, which magnifies the warming of near-surface layers (*6–8*). Since these mechanisms will operate even with the expected rapidity of CO_2 warming, it can be anticipated that average high-latitude warming will be a few times greater than the global mean effect.

Climate models indicate that large regional climate variations will accompany global warming. Such shifting of climatic patterns has great practical significance, because the precipitation patterns determine the locations of deserts, fertile areas, and marginal lands. A major regional change in the doubled CO_2 experiment with our three-dimensional model (*6, 8*) was the creation of hot, dry conditions in much of the western two-thirds of the United States and Canada and in large parts of central Asia. The hot, dry summer of 1980 may be typical of the United States in the next century if the model results are correct. However, the model shows that many other places, especially coastal areas, are wetter with doubled CO_2.

Reconstructions of regional climate patterns in the altithermal (*53, 54*) show some similarity to these model results. The United States was drier than today during that warm period, but most regions were wetter than at present. For example, the climate in much of North Africa and the Middle East was more favorable for agriculture 8000 to 4000 years ago, at the time civilization dawned in that region.

Beneficial effects of CO_2 warming will include increased length of the growing season. It is not obvious whether the world will be more or less able to feed its population. Major modifications of regional climate patterns will require efforts to readjust land use and crop characteristics and may cause large-scale human dislocations. Improved global climate models, reconstructions of past climate, and detailed analyses are needed before one can predict whether the net long-term impact will be beneficial or detrimental.

Melting of the world's ice sheets is another possible effect of CO_2 warming. If they melted entirely, sea level would rise ~ 70 m. However, their natural response time is thousands of years, and it is not certain whether CO_2 warming will cause the ice sheets to shrink or grow. For example, if the ocean warms but the air above the ice sheets remains below freezing, the effect could be increased snowfall, net ice sheet growth, and thus lowering of sea level.

Danger of rapid sea level rise is posed by the West Antarctic ice sheet, which, unlike the land-based Greenland and East Antarctic ice sheets, is grounded below sea level, making it vulnerable to rapid disintegration and melting in case of general warming (*55*). The summer temperature in its vicinity is about −5°C. If this temperature rises ~ 5°C, deglaciation could be rapid, requiring a century or less and causing a sea level rise of 5 to 6 m (*55*). If the West Antarctic ice sheet melts on such a time scale, it will temporarily overwhelm any sea level change due to growth or decay of land-based ice sheets. A sea level rise of 5 m would flood 25 percent of Louisiana and Florida, 10 percent of New Jersey, and many other lowlands throughout the world.

Climate models (*7, 8*) indicate that ~ 2°C global warming is needed to cause ~ 5°C warming at the West Antarctic ice sheet. A 2°C global warming is exceeded in the 21st century in all the CO_2 scenarios we considered, except no growth and coal phaseout.

Floating polar sea ice responds rapidly to climate change. The 5° to 10°C warming expected at high northern latitudes for doubled CO_2 should open the North-

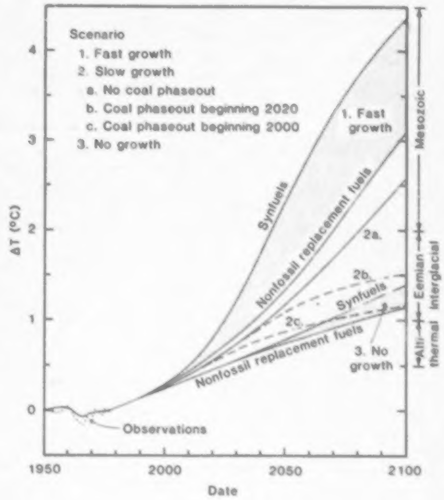


Fig. 6. Projections of global temperature. The diffusion coefficient beneath the ocean mixed layer is 1.2 cm^2 sec^{-1}, as required for best fit of the model and observations for the period 1880 to 1978. Estimated global mean warming in earlier warm periods is indicated on the right.

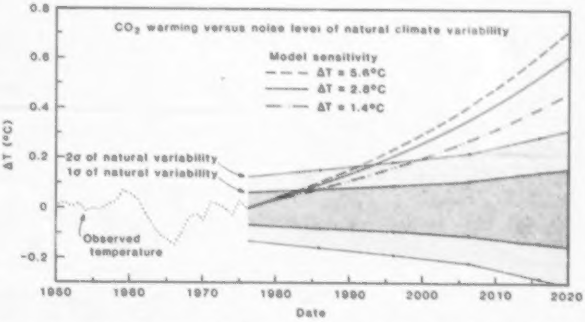


Fig. 7. Comparison of projected CO_2 warming to standard deviation (σ) of observed global temperature and to 2σ. The standard deviation was computed for the observed global temperatures in Fig. 3. Carbon dioxide change is from the slow-growth scenario. The effect of other trace gases is not included.

west and Northeast passages along the borders of the American and Eurasian continents. Preliminary experiments with sea ice models (*56*) suggest that all the sea ice may melt in summer, but part of it would refreeze in winter. Even a partially ice-free Arctic will modify neighboring continental climates.

Discussion

The global warming projected for the next century is of almost unprecedented magnitude. On the basis of our model calculations, we estimate it to be ~ 2.5°C for a scenario with slow energy growth and a mixture of nonfossil and fossil fuels. This would exceed the temperature during the altithermal (6000 years ago) and the previous (Eemian) interglacial period 125,000 years ago (*53*), and would approach the warmth of the Mesozoic, the age of dinosaurs.

Many caveats must accompany the projected climate effects. First, the increase of atmospheric CO_2 depends on the assumed energy growth rate, the proportion of energy derived from fossil fuels, and the assumption that about 50 percent of anthropogenic CO_2 emissions will remain airborne. Second, the predicted global warming for a given CO_2 increase is based on rudimentary abilities to model a complex climate system with many nonlinear processes. Tests of model sensitivity, ranging from the equilibrium climates on the planets to perturbations of the earth's climate, are encouraging, but more tests are needed. Third, only crude estimates exist for regional climate effects.

More observations and theoretical work are needed to permit firm identification of the CO_2 warming and reliable prediction of larger climate effects farther in the future. It is necessary to monitor primary global radiative forcings: solar luminosity, cloud properties, aerosol properties, ground albedo, and trace gases. Exciting capabilities are within reach. For example, the NASA Solar Maximum Mission is monitoring solar output with a relative accuracy of ~ 0.01 percent (*57*). Studies of certain components of the climate system are needed, especially heat storage and transport by the oceans and ice sheet dynamics. These studies will require global monitoring and local measurements of processes, guided by theoretical studies. Climate models must be developed to reliably simulate regional climate, including the transient response (*58*) to gradually increasing CO_2 amount.

Political and economic forces affecting energy use and fuel choice make it unlikely that the CO_2 issue will have a major impact on energy policies until convincing observations of the global warming are in hand. In light of historical evidence that it takes several decades to complete a major change in fuel use, this makes large climate change almost inevitable. However, the degree of warming will depend strongly on the energy growth rate and choice of fuels for the next century. Thus, CO_2 effects on climate may make full exploitation of coal resources undesirable. An appropriate strategy may be to encourage energy conservation and develop alternative energy sources, while using fossil fuels as necessary during the next few decades.

The climate change induced by anthropogenic release of CO_2 is likely to be the most fascinating global geophysical experiment that man will ever conduct. The scientific task is to help determine the nature of future climatic effects as early as possible. The required efforts in global observations and climate analysis are challenging, but the benefits from improved understanding of climate will surely warrant the work invested.

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GEOPHYSICAL RESEARCH LETTERS, VOL. 8, NO. 10, PAGES 1035-1038, OCTOBER 1981

GREENHOUSE EFFECT OF TRACE GASES, 1970-1980

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Abstract. Increased abundances were measured for several trace atmospheric gases in the decade 1970-1980. The equilibrium greenhouse warming for the measured increments of CH_4, chlorofluorocarbons and N_2O is between 50% and 100% of the equilibrium warming for the measured increase of atmospheric CO_2 during the same 10 years. The combined warming of CO_2 and trace gases should exceed natural global temperature variability in the 1980's and cause the global mean temperature to rise above the maximum of the late 1930's.

Introduction

CO_2 absorbs in the 7-14μm atmospheric window which transmits thermal radiation emitted by the earth's surface and lower atmosphere. Increased atmospheric CO_2 tends to close this window and cause outgoing radiation to emerge from higher, colder levels, thus warming the surface and lower atmosphere by the so-called greenhouse mechanism. The CO_2 greenhouse effect has been studied in a series of papers by Manabe (cf. Manabe and Stouffer, 1980) and many other investigators (NAS, 1979). Ramanathan (1975) pointed out that the chlorofluorocarbons (CFCs) also may cause a significant greenhouse effect. Wang et al. (1976) argued that a broad range of trace gases which absorb in the infrared, particularly N_2O, CH_4 and CFCs, may increase as a result of anthropogenic activities, and that their combined warming could be comparable to that caused by CO_2.

Recent measurements confirm that these trace gases are increasing in abundance. We use these measurements and a 1-D radiative-convective climate model to estimate the global greenhouse warmings caused by N_2O, CH_4 and CFCs in the decade 1970-1980 and compare their effect to the CO_2 greenhouse warming in the same period. We include analytic approximations to the results to allow easy modification for improved trace gas measurements. Finally, we compare the computed trace gas warming in the 1970's to observed global temperature change in that decade and to natural variability of temperature on the decadal time scale.

Observed Trace Gas Abundances

CO_2 has been accurately monitored since 1957 (Keeling et al., 1976). Tabular data through 1980 is available for several stations in the GMCC reports (Herbert, 1980) and from the National Climate Data Center. The global mean increase of CO_2 in the 1970's was 12 ± 1 ppm (parts per million).

CFCs have been monitored since the mid-1970's, as tabulated in the GMCC reports. At the beginning of 1980 there were about 180 ppt (parts per trillion) of CCl_3F at Mauna Loa. The CCl_3F abundance was 80 ppt at the end of 1973. Since almost half of the cumulative CCl_3F release to that time was released in 1970-1973 (CMA, 1980), we estimate the CCl_3F abundance at the beginning of 1970 as 45 ppt, and thus the increase in the 1970's as 135 ppt. CCl_2F_2 abundance was ~315 ppt at the beginning of 1980 and ~250 ppt at the beginning of 1977. Just over half of the cumulative prior CCl_2F_2 release was in 1970-1977 (CMA, 1980), so we estimate the CCl_2F_2 abundance at the beginning of 1970 as 125 ppt and the 1970's increase as 190 ppt. Observations at several sites (Herbert , 1980) and unpublished 3-D model experiments which we have made indicate that the difference between the Mauna Loa and global mean values was positive in both 1980 and 1970 with value of the order of 10 ppt. Error in our estimated 1970-1980 CFC increases is not likely to exceed 20% of the estimated increases.

Comparison of CH_4 measurements in 1965-1980 by several different investigators suggests an increase of 1-3%/yr (Rasmussen and Khalil, 1981a,b). Heidt and Ehhalt (1980) showed that some of the reported measurements early in this period were probably systematically too low by 20%, which could account for a large part of the apparent increase. Rasmussen and Khalil (1981a;b) argue that the total available data suggest that CH_4 is increasing about 1.7%/yr. Recent gas chromatograph measurements of Rasmussen and Khalil (1981a,b) indicate an increase of 2±0.5%/yr during 1979 and 1980. Graedel and McRae (1980) measured an increase of 0.1 ppm for 1968-1977, ~0.6%/yr. We examine the effect of a 1970-1980 increase from 1.5 to 1.65 ppm, i.e., ~0.9%/year, as an intermediate estimate. Weiss (1981) measured an increase of 0.2%/yr in N_2O abundance for 1976-1980. This growth rate is consistent with the long-term increase inferred from measurements of stored samples (Weiss, 1981). It is also consistent with the measurement by Rasmussen et al. (1981) of 0.3±0.2%/yr growth for the period 1975-1980. We thus estimate the 1970 N_2O abundance as 295 ppb (Weiss, 1981; Weiss et al., 1981) and the decadal growth as 6 ppm.

We conclude that recent observations confirm that our planet's atmospheric composition is far from being immutable. We recognize that more precise future measurements may substantially modify the estimated changes of specific trace gases. Therefore, we give analytic expressions for the computed greenhouse warmings, so the results can be adjusted in accord with more accurate data.

1-D Radiative-Convective Model

The 1-D RC model uses a time-marching procedure to compute the vertical atmospheric temperature profile from the net radiative and convective energy fluxes. The radiative flux is obtained by integrating the radiative transfer equation over

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*T. Mitchell contributed to this research as a participant in the Summer Institute on Planets and Climate at the Goddard Institute for Space Studies and Columbia University.

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Paper number 1L1506.
0094-8276/81/001L-1506$01.00

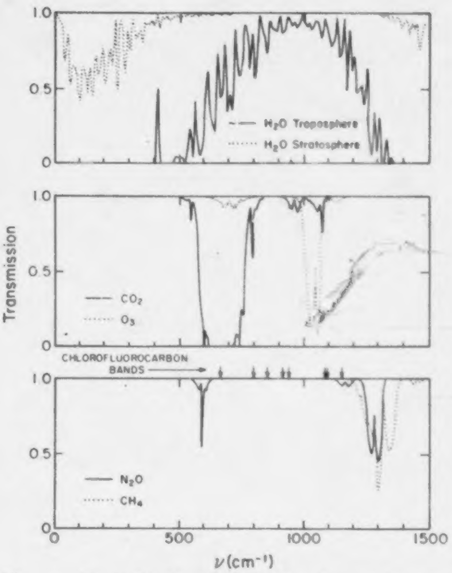

Fig. 1. Transmission of thermal radiation by atmospheric gases for present day abundances. Arrows indicate the locations of CFC bands.

all frequencies, using the temperature profile of the previous time step and an assumed atmospheric composition. The convective flux is the energy transport needed to prevent the temperature gradient from exceeding a preassigned limit (6.5°C/km), which parameterizes effects of vertical mixing and large scale dynamics.

The radiative calculations are made with a method (Lacis et al., 1979) which groups absorption coefficients by strength for efficiency. Pressure and temperature dependent absorption coefficients are from line-by-line calculations for H_2O, CO_2, O_3, N_2O and CH_4 (McClatchey et al., 1973) including continuum H_2O absorption (Roberts et al., 1976). Transmission of thermal radiation by these gases is shown in Fig. 1. Climatological cloud cover (50%) and aerosol properties (Toon and Pollack, 1976) are used, with appropriate fractions of low (0.3), middle (0.1) and high (0.1) clouds. Wavelength dependence of cloud and aerosol properties is obtained from Mie scattering theory. Multiple scattering and overlap of gas absorption bands are included.

Model approximations and uncertainties are discussed by Hansen et al. (1981). The model's equilibrium sensitivity is ~3°C for doubled CO_2. The model includes major feedback effects believed to operate in the climate system. The sensitivity for doubled CO_2 is similar to the global mean sensitivity of 3-D climate models (NAS, 1979). It is widely believed that this equilibrium sensitivity is correct to within a factor of two (NAS, 1979).

A detailed description of the radiative calculations will be given in a separate paper, including comparisons with line-by-line and band model calculations.

Equilibrium Warmings

We computed the equilibrium ($t \rightarrow \infty$) warming for arbitrary changes of the relevant trace gases, and fit the results with an analytic expression:

$$\begin{aligned}\Delta T_{eq}(^\circ C) &= 0.57(CH_4)^{0.5} + 2.8(N_2O)^{0.6} \\ &- 0.057\times CH_4\times N_2O + 0.15\times CCl_3F + 0.18\times CCl_2F_2 \\ &+ 2.5\ln[1 + 0.005\Delta CO_2 + 10^{-5}(\Delta CO_2)^2] \qquad (1)\end{aligned}$$

where the abundances are in ppm except CCl_3F and CCl_2F_2 which are in ppb; the CO_2 amount is in ppm above a reference value of 300 ppm. Equation (1) fits the 1-D model results to better than 5% for abundances $CH_4 < 5$ ppm, $N_2O < 1$ ppm, $CCl_2F_2 < 2$ ppb, $CCl_3F < 2$ ppb, and $\Delta CO_2 < 300$ ppm; the third term corrects for overlap of the CH_4 and N_2O bands.

The sensitivity we find for increase of CFCs from 0 to 2 ppb is 0.65°C, significantly smaller than the 0.9°C obtained by Ramanathan (1975). This difference warrants detailed comparison of the models and assumptions employed, though we have carefully checked our calculations and are confident that they are accurate. It is sufficient for now to note that our conclusions would not be qualitatively affected by the existence of a stronger sensitivity to changes in CFC abundance.

The equilibrium warming for the CO_2, CH_4, CFCs and N_2O added to the atmosphere in the 1970's follows from (1). As indicated in Table 1 and Fig. 2, the 12 ppm increase of CO_2 yields an equilibrium warming of 0.14°C. The other trace gases known to have increased in abundance, CH_4, N_2O and the CFCs, each yield a substantially smaller warming, but their net equilibrium warming is 0.10°C, of the same order as the CO_2 warming.

Other trace gases should not alter this comparison. Ozone warrants special attention, because of its strong band at 9.6μm (Fig. 1) and the possibility of anthropogenic effects on O_3 abundance. The effect of O_3 on surface temperature depends strongly on the altitude of the abundance change. Tropospheric O_3 is more effective than stratospheric O_3 in influencing T_s because the stratospheric temperature responds more or less locally, while the tropospheric temperature is tied to the surface by convection and dynamics. Heath (private communication) estimates that stratospheric O_3 at 30-50 km decreased ~5% in the 1970's. This would cause an equilibrium decrease of T_s by ~0.02. However, anthropogenic effects could increase tropospheric O_3 (Logan et al., 1978; Hameed, et al., 1980); there is observational evidence for a small increase in column-integrated O_3 amount, but the magnitude does not exceed measurement uncertainty (Heath, private communication). Thus the sign of an O_3 influence on T_s is uncertain, but the magnitude of any effect in the 1970's should have been small. Several other trace gases may have increased in the 1970's as a result of man's activities

Table 1. Greenhouse effects of several trace gases.

Species	Arbitrary change			1970-1980 change		
	a_0(ppb)	Δa(ppb)	ΔT_{eq}(°C)	a_0(ppb)	Δa(ppb)	ΔT_{eq}(°C)
CH_4	1600	1600	0.26	1500	150	0.032
N_2O	280	280	0.65	295	6	0.016
CCl_3F	0	2	0.29	0.045	0.135	0.020
CCl_2F_2	0	2	0.36	0.125	0.190	0.034
CO_2	300000	300000	2.9	325000	12000	0.14

(Wang et al., 1976). It seems unlikely that the equilibrium warmings of other gases exceeded a few hundredths of a degree, but that could make the net greenhouse effect of the non-CO_2 gases as great as that for CO_2. Clearly a continuing inventory of atmospheric composition is needed.

Our best estimate of the trace gas equilibrium warming in the 1970's is thus 70% of the CO_2 warming. The major uncertainty is the magnitude of the CH_4 growth, though there is general agreement of an increase in the 1970's. We conclude that the trace gas warming was probably between 50% and 100% of the CO_2 warming in the 1970's.

Expected Surface Warming, 1970-1980

The portion of the equilibrium warming which would be expected to appear by 1980 depends on the effective heat capacity of the ocean. The upper 'mixed' layer (~100 m) of the ocean provides the initial reservoir to be heated by an increased greenhouse effect. If there were no exchange between the mixed layer and deeper ocean, the mixed layer would respond to incremental heating by approaching its new equilibrium temperature, $T_0 + \Delta T_{eq}$, exponentially with e-folding time

$$\tau \sim \Delta T_{eq} Q/f \qquad (2)$$

where Q is the mixed layer heat capacity and f the initial net heating of the surface. For the trace gases (including CO_2) added to the atmosphere in 1970-1980 (Table 1), f is 0.3 W m^{-2} (compared to ~4 W m^{-2} for an instantaneous doubling of CO_2). f is independent of feedbacks and hence τ, like ΔT_{eq}, is proportional to any feedback factors which amplify ΔT_{eq} (Hansen et al., 1981). Thus the relaxation time $\tau \sim 6$ years, obtained from (2) for the above value of ΔT_{eq} and a 70m global mean mixed layer thickness, applies to the model with equilibrium sensitivity ~3°C for doubled CO_2.

The feedbacks make τ large enough that the exchange of heat between the mixed layer and thermocline cannot be neglected, further increasing the time required to reach full equilibrium warming of the surface. The lag in surface temperature response can be estimated with a simple box diffusion model (Oeschger et al., 1975) with instantaneous mixing in the upper 100 m and diffusion into the deeper ocean with diffusion coefficient $k \sim 1\ cm^2\ s^{-1}$. This model, which is consistent with other simple models for heat penetration into the ocean (Thompson and Schneider, 1979; NAS, 1979; Hoffert et al., 1980; Cess and Goldenberg, 1981), leads to the conclusion that only about half of the equilibrium warming for the gases added to the atmosphere in the 1970's should have appeared by 1980. The expected greenhouse warming in the 1970's is thus ~0.1°C, plus residual warming from gases added prior to 1970. The latter increment is probably not more than ~0.05°C, since increases in trace gases other than CO_2 were probably small prior to 1970. The net greenhouse warming expected for the 1970's is thus 0.1-0.2°C.

Observed Atmospheric Temperature Trend

Recent analyses agree that the Northern Hemisphere surface air and tropospheric temperatures increased by about 0.1-0.2°C in the 1970's (Jones and Wigley, 1980; Angell and Korshover, 1978 and private communication; Hansen et al., 1981). The latter authors also analyzed the global mean temperature trend, for which they found a similar increase in the 1970's.

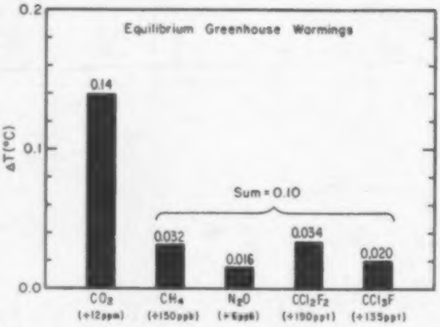

Fig. 2. Equilibrium greenhouse warmings for estimated 1970-1980 abundance increases of several trace gases, based on 1-D RC model with sensitivity ~3°C for doubled CO_2

Normal fluctuations of the smoothed global mean temperature are of the order of 0.1°C for decadal time scales. For example, the standard deviation, σ, of the 5-year-smoothed global mean temperature of Hansen et al. (1981) is 0.1°C for 10 year intervals. Therefore, although the observed global temperature change in the 1970's is consistent with that expected from increased trace gas abundances, the change is too small to be confidently ascribed to the greenhouse effect.

Global warming due to increased abundance of infrared absorbing gases can be expected to exceed natural variability in the 1980's, when the residual warming due to gases added to the atmosphere in the 1970's should appear in observed temperatures as well as about half the equilibrium warming of gases added in the 1980's. The effect of trace gases, including CO_2, is likely to be a warming 0.2-0.3°C in the 1980's. The total temperature rise in the 1970's and 1980's should thus substantially exceed natural variability for a 20-year period.

Discussion

The computed greenhouse warming for reported increases of several trace gases in the 1970's is about 70% as large as that due to the CO_2 increase in the same decade. Despite uncertainties in the abundance increases, we conclude that these trace gases caused a greenhouse warming in the 1970's comparable to that due to increasing atmospheric CO_2. This reemphasizes the conclusion of Wang et al. (1976) that it is important to establish accurate monitoring of a number of trace atmospheric constituents including CH_4 and N_2O.

There is little evidence that these trace gases added much to the CO_2 greenhouse effect prior to 1970. For example, from their absolute abundance we know that most of the CFCs in the atmosphere were added during the past decade. However, the combined growth of CO_2 and other trace gases in the 1970's was sufficient to cause a net computed greenhouse warming for the decade similar in magnitude to natural decadal temperature variability, and the combined warmings in the 1970's and 1980's should exceed natural variability. Indeed, unless the greenhouse warming is counteracted by some abnormal cooling effect, e.g., volcanic activity much greater than usual or a decrease of solar irradiance, the global mean temperature should rise well above the level of the 1930's. Several measurements, especially of trace gas abundances and solar irradiance, are needed during the 1980's to permit cause and effect association of observed warming with the greenhouse gases.

These results underline the importance of understanding man's impact on tropospheric composition. It is now clear that several trace gases significantly impact the radiation and energy budget at the earth's surface and are capable of modifying our climatic environment. It is thus imperative to develop a basic understanding of the factors determining the abundance of such trace gases and their sensitivity to anthropogenic influence.

Acknowledgments. We thank M.B. McElroy, R.A. Rasmussen and R.F. Weiss for helpful discussions, and the latter two authors for preprints of their 1981 J. Geophys. Res. papers.

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(Received July 27, 1981;
accepted September 29, 1981.)

Reports

Global Sea Level Trend in the Past Century[+]

Abstract. *Data derived from tide-gauge stations throughout the world indicate that the mean sea level rose by about 12 centimeters in the past century. The sea level change has a high correlation with the trend of global surface air temperature. A large part of the sea level rise can be accounted for in terms of the thermal expansion of the upper layers of the ocean. The results also represent weak indirect evidence for a net melting of the continental ice sheets.*

Sea level change is of current interest because of its possible sensitivity to climate change. It has been suggested, for example, that global warming due to increasing atmospheric CO_2 could melt the marine West Antarctic ice sheet, raising the global sea level 5 to 6 m (*1*). A sea level rise of as little as 15 cm may double the probability of damaging storm surges on the coast of Britain (*2*). Such a rise would also cause substantial beach erosion and the intrusion of seawater into low-lying areas that are now freshwater regions.

Many processes affect the sea level position measured on shorelines. Among the most important are eustatic sea level changes due to changes in the ocean water volume, caused mainly by the melting or growth of ice sheets, and isostatic adjustments of the earth's crust, caused mainly by ice sheet growth or decay and the associated change in the ocean water mass (*3, 4*). Tectonic movement and river sedimentation can generate local sea level trends comparable to eustatic and isostatic changes, as can changes in ocean currents and prevailing winds, although such trends are of limited duration.

We used tide-gauge measurements to estimate global sea level change in the past century. Data from more than 700 stations were obtained from the Institute for Oceanographic Science, Birkenhead, England. We excluded stations with records shorter that 20 years (a majority of the stations) and stations in seismically active areas such as the Pacific coast of Japan and in rapidly subsiding localities such as Galveston, Texas, and the Mississippi delta. The remaining 193 stations were divided into 14 regions on the basis of geographic proximity and the expected similarity of isostatic or tectonic behavior.

We reduced the individual station records to a common reference point by fitting a least-squares regression line to sea level as a function of time and by defining the zero point to be the value of the regression curve for 1940. The annual mean sea level curves for stations within a geographical region were then averaged to yield a mean sea level curve for each region. We obtained the global mean sea level curve by averaging the regional mean sea level curves, weighting each region equally (excluding the isostatically uplifting region of Scandinavia). Sea level trends, obtained by fitting a regression line through the mean sea level curves, are summarized in Table 1.

We also attempted to remove the long-term (usually 6000-year) sea level trends from the station data in order to obtain short-term sea level fluctuations, which are perhaps more appropriate for correlation with global climate variations in the past century. The cause of the long-term trend is uncertain. It has been argued that as much as 90 percent of it is residual isostatic uplift of continents due to the removal of the Wisconsin ice sheets (*4*). However, the long-term trend may contain a eustatic component, for example, due to a change in volume of the Antarctic or Greenland ice sheets.

The estimates for long-term sea level change are based on ^{14}C dating of measured positions of shoreline indicators in the geologic records, for example, mollusks, corals, and brackish water peats (*5*). The 6000-year time interval was chosen to be as large as possible without approaching the period of the North American and European ice sheets, thus minimizing the effect of errors in the estimated sea level trend. However, for Scandinavia, where there has been a high rate of isostatic uplift since the last deglaciation, we used as a time interval the last 2500 years to improve the likelihood of obtaining a linear trend applicable to the past century. We corrected the dating of sea level positions to use the recent 5730-year estimate for ^{14}C half-life (*6*), rather than the 5570-year standard that had been used for most of the records (*5*), and to account for past atmospheric ^{14}C fluctuations (*7*).

Table 1. Sea level trends, 1880 to 1980, including correction for long-term (6000-year) trends.

Region	Sea level trend, 1880 to 1980			Corrected sea level trend, 1880 to 1980		
	Number of stations	Linear trend (cm/100 years)	95% Confidence limit (cm/100 years)	Number of stations	Linear trend (cm/100 years)	95% Confidence limit (cm/100 years)
West coast, North America	16	10	2	1	8	3
Gulf coast and Caribbean	6	23	4	4	16	5
East coast, North America	32	30	2	30	15	2
Bermuda	1	26	16	1	20	16
West coast, South America	8	19	31	2	−3	3
East coast, South America	5	4	11	2	16	11
Africa	2	32	31	0		
Southern Europe	15	32	2	7	7	2
West Central Europe	7	13	2	5	4	2
Southern Baltic	21	4	2	14	5	2
Scandinavia	47	−37*	3*	10	10	3
Asia	9	4	3	2	22	4
Australia	9	13	3	0		—
Pacific Ocean	15	19	3	6	6	4
Global mean	193	12	1	86	10	1

*Not included in the global average.

[+] to be published in Science , March 26, 1982

The raw global sea level trend that we obtain for the past century is a rise of about 12 cm per century. After subtraction of the long-term trend, the result is a rise of 10 cm per century or 1 mm/year. The inferred long-term trend of 2 cm per century is very small as compared to the long-term trends of 1 m per century or more that are common at times of continental ice sheet growth or decay (*3*).

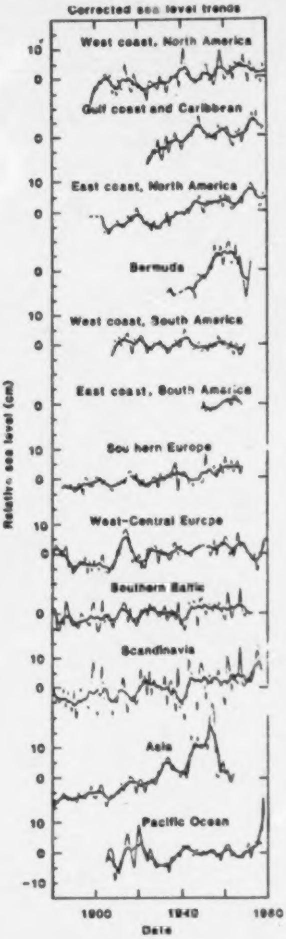

Fig. 1. Regional mean sea level trends. The heavy lines are 5-year running means. Long-range (6000-year) trends have been subtracted.

Evidently the past few millennia have remained too warm to permit ice sheet formation on the North American or Eurasian continents but too cold for substantial melting of the Greenland or Antarctic ice sheets.

We find that sea level rose in the past century in every geographical region except Scandinavia, and, after correction for long-term trends, sea level rose in every region except the west coast of South America where the change is smaller than the uncertainty based on the 95 percent confidence limit. We thus believe that this sea level rise is a true global trend and not, for example, a result of some regional variation in the geoid.

The sea level trend we find is similar to that obtained by Gutenberg [1.1 mm year for the period 1807 to 1939 (*8*)], Fairbridge and Krebs [1.2 mm/year for 1900 to 1950 (*9*)], and Lisitzin [1.12 mm year for 1807 to 1943 (*10*)], even though their studies were based on a much smaller number of tide-gauge stations. However, this rise is much less than the value recently reported by Emery [3 mm year for 1935 to 1975 (*11*)]. Emery included stations in regions of known strong local uplift and subsidence (for example, Scandinavia and the east coast of Japan) and weighted each station equally; the result was that Scandinavia, Japan, and the east coast of the United States were heavily weighted. Emery (*11*) also reported a large increase in sea level (7 mm/year) in the decade 1966 to 1975 on the southeast coast of North America, and Wanless and Harlem (*12*) claim that sea level rose 10 to 14 cm in the past decade in South Florida; their result is based on the displacement of intertidal organisms on seawalls and bridge pilings. Our data (Fig. 1) show the steep rise in that region for 1966 to 1973, but the rise was not global and sea level decreased in the eastern United States for the period 1973 to 1977. Evidently long-term trends cannot be estimated from changes over 5- to 10-year periods for a single region. Even the global average curve (Fig. 2) has notable short-term variability.

The global sea level trend for the past century has some similarity to the trend in global surface air temperature (*13*). To quantify this, we computed the correlation coefficient between our global sea level curve and the global temperature curve of Hansen *et al.* (*13*), obtaining 0.6 when the annual mean curves are used for both quantities and 0.8 when the 5-year running means are used. Most of the positive correlation arises from the general increase in both sea level and

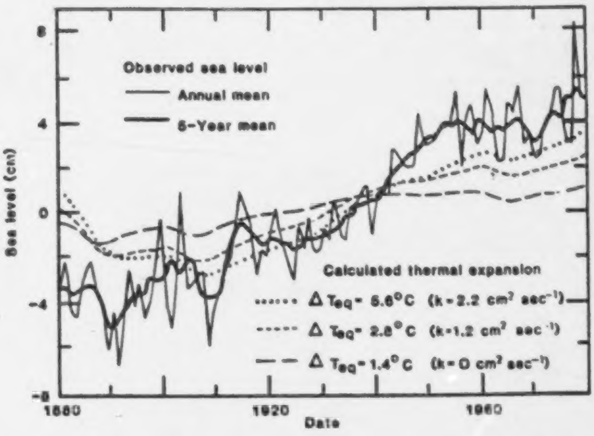

Fig. 2. Global mean sea level trend from tide-gauge data and comparison to the thermal expansion of the upper ocean obtained from the model of Hansen *et al.* (*13*) (see their equation 9 for the heat flux into the ocean). The radiative forcing used was CO_2 + volcanoes + sun (figure 5 in *13*)], but a similar result would be obtained for other forcings that fit the observed global temperature trend; ΔT_{eq} is the equilibrium sensitivity of the model for doubled CO_2, and *k* is the diffusion coefficient beneath the mixed layer.

temperature. Since one might expect a time lag between temperature change and sea level, we fitted a linear relation between our sea level curve and the global temperature trend,

$$S(t) = aT(t - t_0) + b \tag{1}$$

where s and T are the 5-year means of global sea level and temperature, respectively, and t is time. The parameters a and b were obtained by least-squares linear regression, and the time lag t_0 was chosen to minimize the variance between Eq. 1 and the sea level curve. The results were $a = 16$ cm K^{-1}, $b = 0.3$ cm, and $t_0 = 18$ years.

The sea level and temperature records are too short to allow much significance to be attached to this relationship. Nevertheless, it is interesting that the time lag of 18 years is of the order of the thermal relaxation time for the upper layers of the ocean, that is, the layers that are mixed in a time less than or comparable to the thermal relaxation time. This result suggests that part of the sea level rise may be attributable to thermal expansion, a possibility we can test by using the heat fluxes from the one-dimensional model of Hansen *et al.* (*13*). The two primary parameters or "tuning knobs" in that model are the equilibrium sensitivity (say, ΔT_{eq} for doubled atmospheric CO_2) and the rate of mixing of heat into the ocean beneath the mixed layer (specified by a diffusion coefficient k). Figure 2 illustrates the sea level change obtained for three values of the model's equilibrium sensitivity, k being constrained in each case to the value providing the best agreement with the observed global temperature trend of the past century. With the commonly accepted value for ΔT_{eq} of ~ 3°C, about half the observed sea level change is accounted for in terms of the thermal expansion of seawater. We tried other models for the mixing of heat into the ocean and obtained similar results.

We conclude that a large part, but probably not all, of the sea level rise of the past century is due to thermal expansion of the upper ocean. These results therefore also provide weak evidence for a decrease in the volume of the nonocean reservoirs of water. Some ground water levels are known to have receded recently. For example, the huge Ogalalla reservoir in the high plains of the central United States may have dropped by several tens of meters (*14*), equivalent to a drop of a few millimeters of sea level. It seems possible that a sea level rise of a few centimeters could be accounted for in terms of a lowering of global ground water levels. On the other hand, the trapping of water behind dams in the past century may have reduced sea level by 1 to 2 cm (*15*). Thus the net change in the water reservoirs of land areas is probably not a major cause of sea level change.

The magnitude of the global sea level rise therefore suggests that there has been a small net melting of the ice sheets. Although the present evidence is weak, continuation and refinement of this type of analysis is potentially important. As yet, direct observations of ice sheet mass balance are not sufficiently accurate to establish even the sign of any trend (*16*).

A key application of the global sea level trend concerns the potential destruction of the marine West Antarctic ice sheet (*1*). It can be argued that the ice sheet is not close to disintegration, because it survived the Altithermal (~ 5000 years ago) when the global mean temperature was perhaps 1°C warmer than today. However, sea level, as well as temperature, must affect the ice sheet's stability. As indicated above, sea level has been flat, perhaps even rising slowly, over the past 5000 years. With the 10-cm rise of the past century, sea level must now be at or near its highest level since the earlier interglacial, the Eemian 100,000 years ago (*17*).

Thus it is not inconceivable that the situation is near a point at which continued warming and rise of sea level could cause rapid, highly nonlinear disintegration of the ice sheet (*1*). We should emphasize that we have no evidence for such a process. Indeed, the sea level change we have deduced appears to be linear with temperature, and mainly a result of the thermal expansion of seawater. Nevertheless, since sea level is at a high point and rising, the West Antarctic ice sheet warrants close attention.

Continued rise of sea level is likely in the near future, if predictions of global warming (13) are correct. The thermal expansion of sea water may raise sea level about 20 to 30 cm in the next 70 years (18); if slow ice sheet melting increases this by the same factor as in the past 100 years, a sea level rise of about 40 to 60 cm would occur by 2050. Thus we believe that substantial sea level change may occur even without rapid collapse of the West Antarctic ice sheet.

There is a clear need for improved observations. A direct measure of ice sheet growth or decay could be obtained from observations of ice sheet areal coverage and the altitude of the upper surface of the ice sheets that can be monitored by satellite. It is also desirable to measure the changes in the temperature profile in the ocean; these measurements would provide more explicit information on heat penetration and would serve as a crucial test of ocean-atmosphere climate models.

Finally, there is a need for observations and studies of sea level in the 1980's. A sharp global warming trend has been under way since the mid-1960's (*13*), and the current growth of atmospheric CO_2 and trace gases virtually assures that this trend will continue (*18*). The sea level response to this warming should be carefully determined to aid our understanding of the processes and to allow early detection of any nonlinear response.

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2 October 1981; revised 23 December 1981

Mr. GORE. Thank you very much, and thank you for your excellent work. We will withhold questions until we have heard from Dr. Kukla.

Without objection, your statement, Dr. Kukla, will be made a part of the record at the conclusion of your oral presentation, so please proceed.

STATEMENT OF DR. GEORGE J. KUKLA, SENIOR RESEARCH ASSOCIATE, LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

Dr. KUKLA. Thank you, Mr. Gore and Mr. Scheuer.

I have prepared a written statement, and if you agree, I will now summarize the main points of the statement.

You asked me to report on the decrease of the pack ice around Antarctica, the connection of these findings with the carbon dioxide concentrations, and the research which is needed on these and related topics.

Now, I will report on the results which I obtained during the last year, together with my coworker, Gavin, and which were published in detail in Monthly Weather Review and in the journal, Science. I actually gave you copies of those articles.

Mr. GORE. Yes; we have seen that.

Dr. KUKLA. Right.

The research was funded by the climate dynamics program of the National Science Foundation. What we studied were the satellite-derived weekly charts of sea ice boundaries produced by the U.S. Navy, recently in cooperation with the National Oceanographic and Atmospheric Administration.

We also studied the satellite-derived weekly snow charts produced by NOAA, the oceanographic atlases, the sea ice observations made by ships in the past years, and the statistical treatise made by Russians on the surface Earth temperatures in the Northern Hemisphere. These data are more detailed than the studies which we have currently available in our country.

Now, some of that satellite information is quite colorful. As you see, this is the NASA microwave imagery of the Antarctica, so our study is not completely boring in this respect.

So what we found is, that in late spring and early summer, the sea ice along a large segment of Antarctica is considerably less extensive in recent years than it was in the 1930's. I would like to clarify one point because I am afraid that there is a misunderstanding shown in at least in part, of the remarks which I heard here.

Our findings refer to the sea ice, which has nothing to do with the glacier ice sitting on the continent of Antarctica. So the changes which we report are changes in the pack ice. They will produce no change in the sea level whatsoever because of the process that you explained.

Mr. GORE. But, presumably, the same process can be inferred to be happening with the other ice as well.

Dr. KUKLA. There would be an impact, or there may be an impact, of these changes on the ice sheet, but what we are talking about now is the sea ice.

Mr. GORE. All right.

Dr. KUKLA. We also found that, while in the mid-1970's the zonal mean surface air temperatures in the high latitudes of the Northern Hemisphere were cooler throughout most of the year than in the mid-1930's, they were warmer at the time when the seasonal snow and ice cover in corresponding zones dissipates, which is in spring and in summer.

In other words, we have found that the cooling which occurred elsewhere in the 1940's, at least in the Northern Hemisphere, did not occur in spring and summer along the snow and ice margins. Now, this is a geographic zone in which the so-called snow-albedo feedback takes place. Is it understandable what the snow-albedo feedback is?

Mr. GORE. The albedo effect is the reflection from the surface of the ice and snow of some of the heat that comes in the form of lightwaves. Is that what you are talking about?

Dr. KUKLA. Yes; that is how it works. The small increase in the Earth surface temperature along the snow or ice margin would produce a melt in that zone. Now, because snow reflects most of the solar radiation back into space, the surface over snow remains cool. However, when the snow is removed by this melting, the ground gets heated, heats the air, and in turn, then, produces the faster——

Mr. GORE. So it becomes an exponential curve.

Dr. KUKLA. That is correct, yes. That is how it is.

Now, our findings have an implication for the detection of the carbon dioxide climatic impact. This is because several numerical climate models predict that the strongest increase in the shortwave energy absorption resulting from the doubling of carbon dioxide will occur in the snow and ice marginal belt during spring and summer. The energy balance model of Ramanthan and his coauthors predicts the strongest carbon dioxide warming in the Northern Hemisphere to take place at the time and in the latitudes where we actually observed the recent warm anomaly.

This means that the recent changes in the snow and ice marginal belt in spring and summer are in line with the expected result of the increasing carbon dioxide. The link, however, between carbon dioxide and those changes cannot be established with certainty. That is because there are other natural and manmade variables unrelated to carbon dioxide which can influence the climate in the snow and ice marginal belts and produce the observed changes as well.

There are, for example, large year-to-year and decade-to-decade variations in the extent of the sea ice which may be related to the oceanic circulation, and there are similar large changes with the precipitation, including snow.

I would like to underline this difficulty, because to document that any climatic change is due to the carbon dioxide is, of course, a very important task. But it is really very difficult to substantiate such a statement.

At the same time, what we have learned thus far about the seasonal and geographic aspects of the recent climate anomalies is, in my opinion, highly suggestive of the carbon dioxide impact. A significant climate change due to the continuing increase of the atmospheric carbon dioxide in the coming decades is a real possibility.

Now, in my written testimony, I list several other problems with our data sets which, however, I am convinced, do not influence our conclusions.

As for the reliable prediction of the future carbon dioxide climatic impact—future meaning, say, 50 or 60 years ahead—in my opinion, this is not yet possible. The reason is that we still do not understand the background of the variations against which the carbon dioxide-induced climate change is to be measured.

I agree that the numerical climate models have taken us a major step forward toward explaining the physical background of the climate system, but they are still too simplistic to explain the many delicate interactions through which the climate changes.

We are still, for example, unable to explain the climatic developments of the last several years, and this situation dictates the priorities of the carbon dioxide impact research program, which I see as follows:

First, we need to identify all significant variables which are responsible for the climate variations of the past 50 years, not only global but also on a regional scale and to determine the degree to which these affected the climate. This will require a balanced program of monitoring, analyzing, and modeling of the key variables affecting the regional climates.

Second, we will need to project the future changes of the key variables identified as influencing climate.

And, third, we will have to predict the carbon dioxide impact as an integral part of the composite climate system where the variables unrelated to carbon dioxide also change, so we will have to actually reconstruct the whole picture, not only the carbon dioxide picture.

I would like to make one point here, that by approaching this principal objective, at the same time, we will bring a considerable improvement in the season-to-season and year-to-year weather forecasts. I would especially like to call for improvement in our understanding of the processes taking place in the marginal snow and ice belt.

I would also like to see more analyzing of the regional aspects of climate change, especially in the densely populated areas and the major agricultural belts where the social impact of changes is greatest.

We need to expand the analysis of climate change to unconventional variables with high economic impact such as are frequency and intensity of extreme weather conditions like, for example, killing frosts, droughts, and so on.

I thank you for the opportunity to present my testimony, which I hope will help you with your decisions, and I am ready for your questions.

[The prepared statement of Dr. Kukla follows:]

RECENT CHANGES IN THE SNOW AND ICE MARGINAL BELT

STATEMENT OF
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PRESENTED TO THE:
"Joint Hearing on Carbon Dioxide Research
and the Greenhouse Effect,"

HELD BY
The U.S. House of Representatives
Subcommittee on Natural Resources,
Agriculture Research and Environment
and the Subcommittee on Investigations and
Oversight of the Science and Technology Committee
on February 17th, 1982

Dear Mr. Scheuer and Mr. Gore

You asked me to report on the decrease of pack-ice around Antarctica, the connection of these findings to the CO_2 concentration, and the research needed on these and related topics. My statement will summarize the results which I obtained during the last year together with J. Gavin and which were published in more detail in the journals Monthly Weather Review [1] and Science [2]. The research was funded by the Climate Dynamics Program of National Science Foundation. Our results show that the recent summer pack-ice area around Antarctica is less extensive than in the 1930's. We found that the zonal mean surface air temperatures at the time when the seasonal snow and ice cover melts in the high latitudes of the northern hemisphere are higher than in the 1930's. I will discuss the possible relation of the observed phenomena to the rising concentrations of atmospheric CO_2 and recommend the research tasks which I consider of high priority.

Our study was based on the satellite derived weekly charts of sea ice boundaries and concentrations produced by the U.S. NAVY and recently by the NAVY/NOAA Joint Ice Center. We also used satellite derived weekly snow cover charts produced by NOAA, oceanographic atlases of the southern ocean, several publications on sea ice observations from ships and a statistical treatise of the surface air temperatures in the northern hemisphere between 1891 and 1978 published by the Hydrological World Data Center in the U.S.S.R., which is more detailed than the studies available in our country. A detailed listing of the sources and the description of our methodology is contained in reference 2.

Findings

1) We found that in late spring and early summer the sea ice along a large segment of Antarctica between 60°W and 100°E longitude is less extensive in recent years than it was in the 1930's. About four fifths of all the summer ice edge positions reported in the 1930's are north of the corresponding recent average lines and about one third of the reported positions are further north than the maximum extent registered since 1973.

2) We also found that, while in the mid 1970's the zonal mean surface air temperatures in the high latitudes of the northern hemisphere were cooler throughout most of the year than in the mid 1930's, they were warmer at the time when the seasonal snow and ice cover in corresponding zones dissipates in spring and summer (cf. Fig. 1).

3) We therefore tentatively concluded that the cooling which occurred elsewhere since the 1940's did not occur in spring and summer along the snow and ice margins. This is a geographic zone in which the so-called snow-albedo feedback takes place.

Links with the CO_2 Rise

4) The above findings have implications for the detection of a CO_2 climatic impact. This is because several numerical climate models predict that the strongest increase in the short wave energy absorption resulting from the doubling of CO_2 will occur in the snow and ice marginal belt during spring and summer. The energy balance model of Ramanathan, Lian and Cess[3] predicts the strongest CO_2 warming in the northern hemisphere to take place at the time and in the latitudes where the recent warm anomaly was observed (Fig. 2). Our findings on

the southern hemisphere sea ice are in line with earlier published reports on the recent increase in surface air temperatures at many southern ground stations[4] and with the warmer post-war sea surface temperatures around Antarctica as compared to the 1930's. Some of these observations were previously correlated with the CO_2 rise[5].

5) We therefore concluded that the recent changes in the snow and ice marginal belt in spring and summer indicate a warming trend which *may be* the result of increasing CO_2. The reason why the link is still uncertain will be discussed later in my statement.

6) What I believe is established beyond reasonable doubt, is that the climate did change within the last 40 years and that the change was not uniform geographically or seasonally[6]. While most data supporting this statement refer to the annually and seasonally averaged surface air temperatures, the precipitation patterns and other aspects of climate changed as well.[7]

7) The origin of the recent climate change is not known but it is highly probable that the causes are multiple. Based on what we know of the physical behavior of carbon dioxide and based on the results of climate models, it is probable that CO_2 is one of the important factors in recent climate change. Nevertheless, in the middle and high latitudes of the northern hemisphere, the CO_2 increase did not reverse the cooling trend observed in the annual mean temperatures of the last 40 years.

8) Some of the other variables suspected of influencing recent climate on different time and space scales are:

-dust and gases released by volcanic explosions,

-dust and gases released by industry,

-industrial and urban heat,

-land use related changes of surface albedo and evaporation rates,

-variations in solar activity.

Limitations

9) The changes observed along the snow and ice margin can not yet be linked to the CO$_2$ increase with certainty because of the following problems:

a. Other natural and man-made variables unrelated to CO$_2$, such as those listed in paragraph 8, can influence the climate in the snow and ice marginal belts and produce the observed changes. We do not know enough about the processes taking place in these zones to reliably differentiate the climatic impact of CO$_2$ from that stemming from other causes.

b. There are large year-to-year and decade to decade variations in the extent of the sea-ice which some climatologists believe result from the shifts in oceanic circulation. For example the recent decrease in the summer sea ice area around Antarctica between 1973 and 1980 by 2.5 mill sq. km, which followed an episode of sea ice growth between 1968-1972, may be to a large degree due to such a short term variability. There are similar large variations in precipitation including snowfall.

10) I mentioned these limitations to underline the difficulties of documenting, that any climatic change is due to increase of CO$_2$. Such proof is extremely important, but very difficult to substantiate. At the same time, what we have learned thus far about the seasonal and geographic aspects of the recent climate anomalies is in my opinion highly suggestive of the CO$_2$ impact. A significant climate change

due to the continuing increase of the atmospheric carbon dioxide in the coming decades is a real possibility.

11) Currently our observations cover a relatively short time span and are geographically limited. For example the ship observations from the 1930's are available in sufficient density from part of the southern ocean only, and may not be representative of the seas surrounding Antarctica as a whole. Also, differences may arise between some ship observations of the sea ice edge in the 1930's and the modern ones based on satellite data.

In the published articles [1,2] we compared only two pentads to illustrate the change of the surface air temperatures in the northern hemisphere. Subsequently we confirmed these trends using larger sampling intervals (10 and 24 years) and making comparisons to the 1931-1978 average.

The zonal mean temperatures in the northern hemisphere were taken from a published reference[8] for which the original input information is unavailable. Therefore we were unable to test the data quality and representativeness. However, T. Barnett[9] at Scripps Institute of Oceanography made a comparison with the NCAR tapes and found reasonable agreement for the land-dominated middle and high latitudes to which our results refer.

Since the zonal mean temperature departures are residuals from local temperature anomalies of both signs, it would be desirable to determine the anomalies along the shifting snow and ice margins in more detail.

Projections of the Future CO_2 Impact on Climate

12) In my opinion a reliable prediction of the future CO_2 climatic impact is not yet possible. This is because we still do not understand the background of variations against which the carbon dioxide induced climate change is to be measured.

Although the numerical climate models have taken us a major step forward toward explaining the physical background of the climate system, they are still too simplistic to explain the many delicate interactions through which the climate changes.

Our predictions of climate 100 years ahead would be more reliable if we first accurately explained the climatic developments of the last 50 or so years.

13) This situation dictates the priorities of the CO_2 impact research program, which I see as follows:

-First, to identify all significant variables which are responsible for the climate variations of the past 50 years on regional as well as global scales and to determine the degree to which they affected climate. This will require a balanced approach to monitoring, quantitative analyzing and modeling of all key variables affecting regional climates.

-Second, to project the future changes of the variables identified as influencing climate.

-Third, to predict the CO_2 impact as an integral part of the composite climate system, where the CO_2 variables unrelated to CO_2 also change.

14) Some previous strategies placed strong emphasis on the research of the CO_2 impact only, assuming that other variables in the climate system will not alter significantly. In my opinion such approach is short sighted.

Arguments were also made, that other contaminants released by burning of fossil fuels, reside in the atmosphere for a relatively short time, have as yet only regional distribution, and therefore have no climatic impact. I disagree since the global climate is a composite of regional climates, just as the global climate change is an integer of regional climate changes. Since most of the world's population happens to live and raise food in the regions directly affected by the release of industrial pollutants, we should pay more attention to the regional aspects of climate change.

15) By approaching our principal objective, the prediction of future climate, we also will necessarily bring a considerable improvement in the season-to-season and year-to-year forecasts. To reach the goal, I think we need substantial improvement in several areas. Among these are:

-observing, monitoring, physical understanding and modelling of processes taking place in the marginal snow and ice zone. It is especially important to gather data needed for improvements and verifications of numerical climate models,

-analyzing of regional aspects of climate change especially in the densely populated areas and in the major agricultural belts, where the social impact of the changes is greatest,

-expanding the analysis of climate change to unconventional variables with high economic impact such as frequency and intensity of extreme weather conditions (heavy rains, killing frosts, droughts, etc.).

Summary

In summary we found that the cooling which affected the middle and high latitudes of the northern hemisphere since 1940's is not present along the melting snow and ice margins, where some climate models predict the strongest impact of CO_2 on the surface energy exchange. This finding is an indication that the increased concentration of carbon dioxide at present levels is already influencing the climate system.

More data needs to be gathered and numerical climate models significantly improved before a reliable prediction of future climate will be possible.

I thank you for the opportunity to present my testimony, which I hope will help in making your decisions. I'll be glad to answer any questions you might have.

Lamont-Doherty Geological Observatory

February 11, 1982

George J. Kukla

GK/bh

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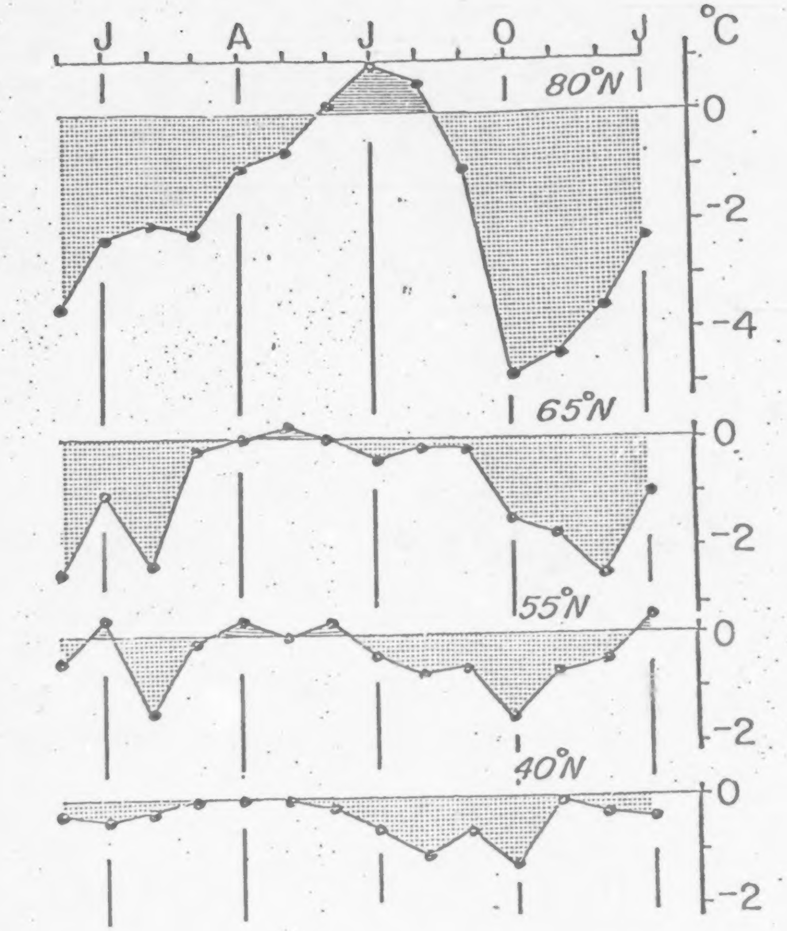


FIGURE 1

Differences of zonal mean monthly temperature in °C between the 1934-38 and 1974-78 pentad in 5° wide belts centered at the latitudes indicated. The recent pentad is predominantly cooler.

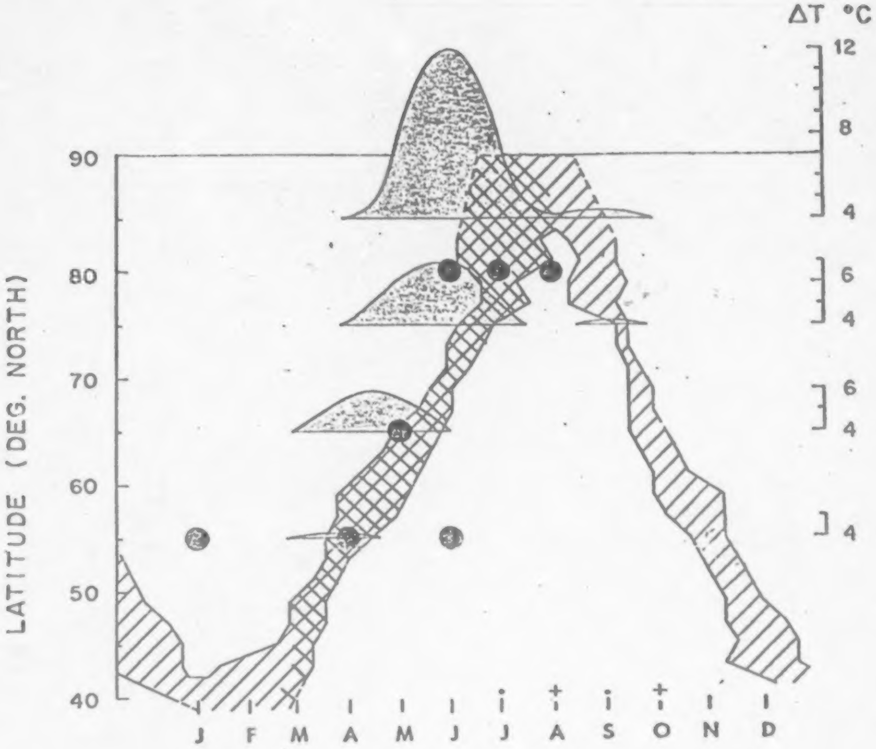


FIGURE 2

Association of recent positive temperature anomalies (full circles) with the belt of melting snow (cross hatched) and the CO_2 sensitive zone of Ramanathan et. al.(3)(stippled). The snow margin is defined as the zone where the 1974-1978 mean weekly surface albedo was between 33 and 66 percent of the multiyear range. Intervals along 55°, 65°, 75° and 85°N, where Ramanathan et. al. (3) predict an increase of zonal mean temperatures larger than 4°C due to CO_2 doubling, are stippled. The scale of the predicted temperature increase is shown on the right.

Mr. GORE. Thank you very much. Thank you both.

Let me ask you, first of all, Dr. Kukla, how would you measure the extent of the ice melt from the 1930's to the present day? You have just completed these measurements. Do you measure ice in terms of cubic miles? What is your unit of measurement?

Dr. KUKLA. Square miles. But, generally, we have to use square kilometers now because, you know, the journal Science wants it that way.

Mr. GORE. Well, can you convert it to square miles?

Dr. KUKLA. Oh, yes.

Mr. GORE. Or use square kilometers. How many square kilometers are we talking about?

Dr. KUKLA. We are talking about, at the end of November and December, the peak summer season in the Anarctic area, a change of some 2 and a half degrees of latitude, which means a belt of, say, 250 kilometers or 300 kilometers in width, all around the——

Mr. GORE. All around the pole.

Dr. KUKLA. Yes; the belt, around Antarctica. So, it is a considerable figure.

Mr. GORE. Well, now, what I am trying to get at is the difference between the 1980's and the 1930's.

Dr. KUKLA. Right, 1970's and the 1930's.

Mr. GORE. Yes.

Dr. KUKLA. That would be it. In the 1970's, we see that the belt some, say, 300 kilometers wide, is actually now in summer occupied by ocean rather than by ice, which was the situation in the 1930's.

Mr. GORE. So you are talking about an amount of ice in Antarctica that has melted already. You are talking about a band 180 miles wide circling the continent of Antarctica. That is the amount that has already melted?

Dr. KUKLA. That process is not continuous. There are large oscillations from one year to another. We took the average extent of ice in the satellite decade, the time when we have the satellite data, and we again took as many years as we could have obtained from the 1930's with the ship records, which was practically the whole decade, and then we compared these two averages.

Mr. GORE. Yes, and when you take out the fluctuations from summer to winter and from year to year and compare the average for the decade of the 1930's to the average of the decade of the 1970's, the difference in that average is a band of ice 180 miles wide circling the continent of Antarctica that has melted, presumably, since the 1930's.

Dr. KUKLA. Yes. We do not have data for the whole of Antarctica, I mean, for all the circumference of Antarctica, because the ships were not coming frequently enough to the other parts. But we have a pretty large segment.

Mr. GORE. I see.

Dr. KUKLA. From that segment, we assume that a similar thing happened——

Mr. GORE. All the way around.

Dr. KUKLA. Yes.

Mr. GORE. All right. Now, that is one piece of evidence that has become available in the last 6 months. Mr. Hansen, you have provided two more pieces of evidence. First, with respect to temperature, you are testifying that in this century, the temperature has gone up worldwide 0.4 degrees Centigrade. Again, this is difficult to measure because there are such fluctuations from year to year, anyway; it is hard to step back and see the longer trend.

But you have now done that at NASA, and you are saying that it is 0.4 degrees Centigrade, since 1880, is that correct?

Dr. HANSEN. That is right.

Mr. GORE. Now, the second piece of evidence that you have given us is that the sea level has gone up, what, about 4 inches?

Dr. HANSEN. That is right, 10 centimeters or 4 inches.

Mr. GORE. And that if this process continues, it could go up 20 feet?

Dr. HANSEN. Well, that would require melting the entire West Antarctic ice sheet, and that is a possibility. Some scientists think that, if it begins to warm in the region of the West Antarctic ice sheet, pieces of the ice sheet will begin to break off and, in the process of wave action, the crashing of icebergs against ice sheets, it could disintegrate rapidly.

But the weight of opinion in this scientific field is that it would probably require a couple hundred years for that to happen.

Mr. GORE. Now, the periods of time discussed by earlier witnesses was 50 to 60 years. Might we see dramatic shifts in climate as between different latitudes in the U.S. Midwest, for example, before that 200-year timeframe?

Dr. HANSEN. Yes; I certainly think that is possible. Most of the climate modeling has been done with a simple test case in which the amount of carbon dioxide in the atmosphere is doubled. The models show that this would have very large climate effects.

With the rate that energy use is increasing at this time, it probably will be sometime in the middle of the next century, about 75 years, before we would reach that point. It is very possible that the climate changes before that time will also be large, but there has not been a significant attempt to model the transient climate changes that you would expect as carbon dioxide slowly increases at the rates that it currently is increasing.

Mr. GORE. What has been the reaction of the scientific community to these rather startling results that you have recently reported?

Dr. HANSEN. In the case of the temperature increase, there has been confirmation from two different groups, who get quite similar results to that which we report. In the case of the sea level effect, there was, in addition to our paper which was published recently in Science, another paper by NOAA researchers which discuss a somewhat larger increase in sea level. The cause for the differences in our results remains to be determined, but there is general agreement that there has been a sea level rise. So both empirical pieces of evidence are agreed upon by scientists.

Mr. GORE. Is it fair to say that, as a result of the physical evidence that has been presented within the past 6 months, there is now a consensus within the scientific community that the greenhouse effect is in fact occurring?

Dr. HANSEN. That is a difficult question. I think there is a consensus that the greenhouse effect is real and that substantial climate change will accompany large changes in atmospheric carbon dioxide. Whether that greenhouse effect is now large enough to be noticeable with these beginning indicators, these first indicators, I think would be debated by some scientists, because of the natural variability of the climate. As I showed in my first vu-graph, there are other factors which influence global climate. Until we have a handle on those, it is perhaps premature to be very definitive about the greenhouse effect already occurring.

Mr. GORE. But the consequences of the effect, if it is real, are so incredibly unthinkable that we ought to get a handle on the problem. Is that your view?

Dr. HANSEN. That certainly is my view, yes.

Mr. GORE. So you would not advise us to dramatically cut back the efforts in the scientific community to find out whether our Nation and the other nations of the world are facing this problem or not?

Dr. HANSEN. No. As I discussed in my testimony, there are several difficult problems which need to be resolved in order for us to have a good handle on the problem and to be able to predict the future climate consequences.

Mr. GORE. It seems to me, Mr. Chairman, that it might be a good idea for our two subcommittees to explore the possibility of proposing another International Geophysical Year to immediately organize international efforts to assess the extent of this problem, to set up the monitoring stations that have been advised, to improve our measurements on the ice pack and the sea level, and satisfy ourselves that it is not occurring, because, otherwise, the challenge to our country and other countries to take steps that would solve this problem are such a massive challenge that we might not be able to do it if we do not get started right away.

So I think we ought to step up our efforts to find out whether in fact the problem is real, and I think it ought to be done on an international basis.

Mr. Chairman?

Mr. SCHEUER. Well, thank you, Mr. Chairman. I was very much impressed with the testimony of the two witnesses. In effect, they sort of compound our problem of knowing what to do, the order of magnitude that ought to be done, the time frame in which we ought to do it in order to provide the knowledge base to take specific acts.

We hear from you that it would be premature to be very definitive; yet we have heard from Dr. Calvin that the problem is here and now, and that if we let it go very much longer without a coherent, well structured program on almost a global basis——

Dr. HANSEN. Excuse me. I think that perhaps my comment may not have been clearly stated. I believe the reality of the greenhouse phenomenon is clear. If we look at Mars, which has a small amount of carbon dioxide, and Venus, which has much more than we do, we have nice examples which prove the reality of the phenomenon beyond any doubt.

Doubt remains as to the magnitude and the rate at which the climate change will occur and the changes that will occur on the very important regional scale. A global temperature rise of a couple of degrees is important, but what does that mean for different regions? That is a much more difficult problem, and the climate models are not yet able to attack that problem with all the assurance that we would like.

Mr. SCHEUER. Well, of course, it is that kind of data that we urgently need. Congress needs to create a national consensus that would act and perhaps lay on costs for the kind of programs Dr. Calvin was describing and also to create the consensus around the world, particularly in Russia and China, to act cooperatively with us.

We are going to have to get more specific information. We have to quantify the order of magnitude both of the danger and the time frame in which we have to meet the danger.

You say, for example, that the greenhouse effect is real. Can you tell us how much of that is accounted for by carbon dioxide and how much of that is accounted for by these trace atmospheric gases that you discussed—methane, nitrous oxide, and the freons?

Dr. HANSEN. I can say something about that, but as I mentioned, it is very important that we have better measurements of these other trace gases, and in fact it is important to also try to reconstruct what these trace gases were in the past, and it may be possible to do that. For example, by looking at astronomical plates that contain observations taken during the past 100 years. We can see the absorption lines produced at different wave lengths by these gases and try to deduce what the abundance of gases was.

But it appears likely that on the 100-year time scale, the lion's share of the greenhouse effect was and is due to carbon dioxide because these other gases have only been added significantly during the past couple of decades as far as we know.

The chlorofluorocarbons, in particular, are entirely man-made. Their trade name is freons. They are used in spray cans and in refrigeration, and they have only been produced during the last two decades.

Mr. GORE. Will the chairman yield?

Mr. SCHEUER. Of course.

Mr. GORE. Is there a point at which the dynamics of this process take over? Is there a trigger point, is what I am asking.

Dr. HANSEN. That is a difficult question. I am somewhat avoiding the question, but one thing that I state in my written testimony is that, based on our current knowledge of the rate of mixing of heat into the ocean, there is a very good possibility that the largest part of the greenhouse effect for the gases already added to the atmosphere has not yet appeared at the surface because it requires a few decades for the upper layers of the ocean to warm. Therefore, we may already have in the pipeline a larger amount of climate change than people generally realize.

Mr. GORE. Dr. Calvin, could I ask you to speak up and address that question? Is there a point where we trigger the dynamics of this process, and if so, when do we reach that stage? Hold the microphone, if you would, or be seated at the table.

Dr. CALVIN. Dr. Hansen has already implied the answer to this. The solubility of the carbon dioxide in the surface of the sea drops as you raise the temperature. Now, as the temperature warms up, the sea will warm up, more carbon dioxide will come out, and that is a feedback, a positive feedback mechanism.

He has already alluded to that, and the question is, when does it take off? I think that is what you are asking.

Mr. **Gore**. Yes. When is the trigger point?

Dr. **Calvin**. I wish I knew. It could be close.

Mr. **Gore**. What do you mean by close, 10 or 20 years?

Dr. **Calvin**. Oh, no, don't push me like that.

Mr. **Gore**. Fifty? A hundred?

Dr. **Calvin**. Ask him. He is a better meteorologist than I am. My feeling is that it is——

Mr. **Gore**. I want to know whether I am going to face it or my kids are going to face it.

Dr. **Calvin**. Well, I think your kids are likely to face it. I don't know whether you will or not. You look pretty young; you might do it. [Laughter.]

Mr. **Scheuer**. How long do we have?

Dr. **Calvin**. I think Dr. Hansen will agree, that kind of a situation is already upon us. I mean, I did not realize there was that much lag in the system as he just implied. I thought it was a little tighter than it is.

Dr. **Hansen**. One of my recommendations is with regard to heat storage and transport in the ocean, because it is very important to understand that lag.

I think the answer to your question depends upon the magnitude of the climate effect with which you are concerned. I think that within 10 or 20 years, we will see climate changes which are clearly larger than the natural variability.

As far as the very large climate changes, that is probably for our children and grandchildren.

Mr. **Scheuer**. Will the chairman yield?

Mr. **Gore**. Yes.

Mr. **Scheuer**. The impact will be hitting our children and grandchildren if we do nothing now. How soon do we have to act as this exponential curve goes its way, to short circuit that process? Do we have a decade or two decades?

Dr. **Hansen**. We would first need to establish what is the allowable level of greenhouse gases. As I also mentioned in my written testimony, there is substantial uncertainty in regard to the greenhouse effect, even though the climate models agree that there is a large climate change.

For example, the models of Dr. Manabe at Princeton, indicate a warming of 2 degrees, Centigrade, for a doubling of carbon dioxide, while our models indicate 4 degrees. That range of uncertainty is very large. If his result is right, then you would have to have 900 parts per million of added carbon dioxide before you would get a warming of 10 degrees in the vicinity of the West Antarctic ice sheet, while our result implies that you need only 300 parts per million of carbon dioxide, or equivalently 200 parts per million plus the trace gases.

I think we are already at a point where it is going to be difficult to avoid 200 parts per million of added carbon dioxide.

Dr. **Calvin**. Did you say added carbon dioxide, because we are already up there.

Mr. Gore. We are at 340 now, and you are talking about 540——

Dr. **Hansen**. I am talking about 500, yes.

Mr. GORE [continuing]. Before it becomes an inexorable process.

Mr. SCHEUER. I take it, when you say——

Dr. HANSEN. Excuse me. But you also must take account of the fact that the systems that produce carbon dioxide have a long lifetime of their own which you cannot turn off instantaneously. To change from one fuel to another has typically taken four to five decades.

Mr. SCHEUER. Well, this is exactly what I am getting to. What Dr. Calvin is suggesting is a real carbon change in our energy production national policies, and they would take decades to effect. How soon do we have to start making these changes in order to bring the increase in temperature down to tolerable levels?

I suppose, if it were 1 or 2 degrees per century, that would be within the range of human adaptability, but we are pushing beyond the range of human adaptability.

Dr. HANSEN. Yes.

Mr. SCHEUER. How soon do we have to have the data base in order to create the consensus and the institutional framework to vastly change our national patterns of energy production?

Dr. HANSEN. You are asking a question which I do not think any scientist can answer reliably, but my opinion is that time is very soon.

Mr. SCHEUER. Please come to the table, Dr. Calvin.

Dr. CALVIN. My opinion is that it is past.

Mr. SCHEUER. No, grab the microphone.

Dr. CALVIN. Well, I have just said it. I think that it is already later than you think.

Mr. GORE. Well, thank you both very much for your very dramatic testimony, and we appreciate your assistance to the subcommittees here today.

Dr. Kukla, did you have something to add?

Dr. KUKLA. Yes; I would like just to make one point. The Southern Hemisphere change is not that interesting, you know, from the point of view of what we were doing. We were much more excited, so to say, by the exception that we found in the Northern Hemisphere, where over the last 40 years we are generally looking at cooling. But there was an exception in the right place and at the right time when the carbon dioxide is actually expected to have the effect.

Now, this is with a relatively low level of the carbon dioxide concentration in the atmosphere, which means, you know, with higher levels, we should expect an expansion of that effect over much larger areas.

Mr. GORE. Well, to summarize your testimony, you are telling us that, first of all, the greenhouse effect is real. Second, you are telling us that there are areas of uncertainty that remain, particularly about what the effects will be, how extensive they will be, and how long a period of time will pass before they are undeniable.

As a result, it seems to make sense for this country to make greater efforts to find out the answers to these questions, and I take it you would not recommend that we stick our heads in the sand and cut back on our effort to find answers to those questions.

Dr. HANSEN. That is certainly an accurate statement of my views, yes.

Dr. **Kukla**. Correct.

Mr. **Gore**. All right. Thank you both very much.

Our final panel is from the Department of Energy, James S. Kane, Deputy Director of Energy Research, and Frederick Koomanoff, Director of the Carbon Dioxide Research Division with the U.S. Department of Energy.

Without objection, the entire text of your prepared statements will be made a part of the record at the conclusion of your oral presentations.

Dr. Kane, I understand you have a short statement, and then Mr. Koomanoff has a somewhat longer statement. We would invite you both to summarize if you wish, and we will begin with you, Dr. Kane. Welcome.

STATEMENT OF DR. JAMES S. KANE, DEPUTY DIRECTOR OF ENERGY RESEARCH, DEPARTMENT OF ENERGY

Dr. **Kane**. Thank you, Mr. Chairman.

I will do exactly what you said, with your permission, my formal remarks shall be entered into the record. I will give you a brief oral summary and then finally turn it over to Mr. Koomanoff, who will present the details of our program.

Since this committee is very knowledgeable on this subject and has become even more knowledgeable as the result of witnesses today, I am going to spend, very little time on reviewing what is the problem. However, having said that, I am going to make a few points.

First, I would like to congratulate you on your choice of witnesses. There is almost nothing they said I would disagree with. I will be very careful to point out where I do, but I think they did give you an excellent insight into the technical aspects of the problem.

Mr. **Gore**. The Department of Energy agrees with the witnesses' description of the problem?

Dr. **Kane**. I did not quite say that, but I think they are excellent witnesses. [Laughter.]

And I agree with almost everything they said.

Mr. **Scheuer**. Do you share their sense of urgency?

Dr. **Kane**. I will try to cover that in my remarks in a minute.

Now, what we all agree on, without question, is that carbon dioxide is a trace gas. It is increasing. We have good measures on how it has increased. The increase is almost exclusively due to man's activities. You can quibble on what part is due to deforestation and what part combustion of fossil fuels, but the fact is, it is man's activities that are doing it. So we all agree on that.

The second thing we all agree on is that carbon dioxide is a classic greenhouse gas. That is a scientific fact that is not even open for argument. As the pictures show—the ones you had and the one Dr. Calvin showed—it absorbs in the long wavelengths, it is transparent in the shorter ones, and therefore it leads to the greenhouse effect.

The other thing we all agree on is that fossil fuels and their increased use are the chief concern for the future carbon dioxide trend. As was pointed out by almost every witness, the fossil fuels are not all the same in this respect, synthetic fuels being much the worse. It is not just because they have a higher ratio of carbon to hydrogen; it is also because the processes by which you make them are rather wasteful than from a thermodynamics sense.

So to get a certain amount, Dr. Calvin said, into your house, from synthetic fuels produces over twice as much carbon dioxide as if you burned naturally occurring natural gas.

Having said what we agree on—let's get into the things that are not quite as well understood and about which we have far less certainty. Going from the concentration of carbon dioxide, which is a given, to the effect on climate is not nearly as simple as perhaps some of you have been led to believe. It is an extremely difficult and complex problem. It is complex in two ways.

One, the physics is not understood. I think Dr. Hansen pointed out excellently how it is not just a fact of the absorption of carbon dioxide. There are other means by which the Earth can lose energy, such as a rising of the altitude at which clouds occur, changing the albedo due to clouds. So it is a very complex situation, and even if you understood all the physics, to go from that to a state where you can predict, on a regional scale, what the climate will be involves applied mathematics and large computations. There are not too many people in the world that do calculations of this size. Such calculations are run on the most modern computers such as the Cray II or Cyber, and there just aren't many of those, nor the skilled people to do that kind of thing. The use of computer models is a very important subject, but exceedingly complex, and one that has to be continually checked against real data.

I was in a different area for a number of years using big computer calculations. They have so many variables, you have to continuously go back and normalize them against real observations. Otherwise, the combination of a number of variables that you have treated not quite right can wind up giving you problems.

So my point on these two things is that—and I think again Dr. Hansen said this very well—the sensitivity of climate change to CO^2 increase is an open scientific question. I am not saying there is no sensitivity, but the exact size of it—how much temperature change do you get for how much carbon dioxide and where changes will occur is a question we do not know the answer to, and you certainly saw that in Dr. Hansen's remarks. He puts uncertainties on them; in his text, he also puts a factor of uncertainty in. So, what the effect will be if the carbon dioxide does increase is not an open and shut case.

I am not saying I know the answer or that it is hopeless. I am saying that we all, as a community, must work toward a consensus maybe.

Mr. **Gore**. So are you saying we need to make greater efforts to get those answers?

Dr. **Kane**. Exactly, yes.

Mr. **Gore**. Well, why are we making fewer efforts to get those answers?

Dr. **Kane**. Again, I will come to that in a minute.

The position of the DOE—and I think this is my personal position, too—is that if we cannot assess the severity exactly, it does not mean that it is not a problem. The potential impacts, as you have said and everybody up here has said, are so great that it would be extremely imprudent to say, because we do not know there is a problem yet, we will assume that there is no problem. We are not saying that. We all agree that it is not a problem that we can measure its magnitude, exactly, but certainly it would be idiotic to say, since we have not proven it is a problem, there is no problem, and we are certainly not operating from that basis.

Our program in the next year is going to be focused on the very factors that I think you heard most about from the last two witnesses: a better understanding, a reduction of uncertainties, an improvement in our capability of modeling. Therefore, in the budget it is $8 million for the next fiscal year budget, we have focused on this kind of core item.

They really boil down to the three chief elements: first, the carbon cycle—again, your witnesses pointed out there are still unknowns of the sources and sinks of carbon, and those introduce uncertainties into the system; second, climate prediction—including the question of first detection. Those are the questions we are giving the highest priority to in our budget this year.

And a third one that has not been mentioned except rather indirectly by Dr. Calvin, is the direct effect of CO_2 on vegetation. The one thing I guess we would all conclude, is that as the concentration of carbon dioxide, which is the food of plants, increases, it is going to affect their growth and determining in what way, exactly, will require to research.

So that is the focal area of our program. I will return to our budget in just a minute.

We are not the only agency, needless to say, involved in this. We are active partners with the NSF, with NOAA, with Department of Agriculture, USGS, EPA, and the National Bureau of Standards. We work closely with these agencies to try to pull this all together across the Government. The mechanism through NOAA is the National Climate Program Office. The Climate Program Office has a standing committee, the Interagency Committee on CO_2 and Climate, and it is chaired by Mr. Koomanoff.

There is also a great deal of international interest and activity in carbon dioxide research.

Finally, as I mentioned, our budget for fiscal year 1983 requests $8 million. This represents the reality of two conflicting factors: budget stringencies and the importance of a recognized problem. We believe it makes sense to concentrate on the better science aspect of this and defer the less central issues.

Now, let me depart from what I intended to say for just a minute. I told you I would take slight issue if it turned out that the witnesses said things I did not fully agree with. The sensitivity of climate of CO_2 concentration is clearly unknown. That is the first area I want to point out that needs more research.

The second thing that affects a lot of these predictions you hear is the rate at which the nations of the world will actually burn fossil fuels. People have a tendency to think exponential curves go on forever, and they put in a constant growth rate which seems to them small, but they let it go on.

Mr. Koomanoff will show you later what the actual market has done to the consumption of fossil fuels. A few years ago, it was very fashionable to assume 4 percent per year growth. Well, that is a doubling time of a little over 16 years, or something like that, so that is a very fast growth rate and one society probably cannot sustain.

The market forces, without any intervention from policy, have reduced the growth rate worldwide to about half what the experts were predicting just a few years ago. Mr. Koomanoff has a slide on this, which is hard data again, it is not speculation. So what we have chosen to do is focus on the central issues and not get into the prediction of impact, which I personally do not think we know enough about to make exact predictions. I think it would produce paper that would be of little use.

Second, we have also chosen to pull out, at least temporarily, of what your witnesses last year alluded to as research giving resiliency, and I will be glad to discuss that in answer to your questions.

In summary, we think this is an important problem. We are going to focus on the basic issue of understanding the science and uncertainties in the next year so we can move forward, with more credibility. You are certainly going to need a great deal of credibility before you start the actual earth-shaking type of policy decisions that will be required if, indeed, these predictions you heard today are true.

So that concludes my testimony. As you certainly know, I will be glad to answer questions now or later, at your pleasure, and then I would like to turn it over to Mr. Koomanoff.

[The prepared statement of Dr. Kane follows:]

STATEMENT OF JAMES S. KANE
DEPUTY DIRECTOR OF ENERGY RESEARCH
DEPARTMENT OF ENERGY
BEFORE THE
NATURAL RESOURCES, AGRICULTURE RESEARCH AND
ENVIRONMENT SUBCOMMITTEE
AND THE
INVESTIGATIONS AND OVERSIGHT SUBCOMMITTEE
HOUSE SCIENCE AND TECHNOLOGY COMMITTEE
MARCH 25, 1982

Thank you Chairman Scheuer, Chairman Gore, and Members of the Subcommittees. The Department's testimony will be given in two parts. I will provide a brief overview and present the Fiscal Year 1983 budget request. Fred Koomanoff, Director of the Carbon Dioxide Research Division, will then discuss the program in greater detail.

Your Committees are surely aware of the Department's program on CO_2 and the importance of the issue. In fact, much of the progress we have made is due to the interest and support of your Subcommittees. I will, therefore, give you only a brief description of the factors which make our research necessary.

Worldwide, mankind is increasing the CO_2 content of the atmosphere by two processes: deforestation and the burning of fossil fuels, the latter being by far the more important. There are reliable measurements of this increase from 315 to 338 parts per million. We do not know, however, the exact effects that this increase has caused, nor can we predict future effects with confidence. The combination of all the processes that make up the climate--global and especially regional--is one of extreme complexity.

The essence of our program, as you shall hear, is to achieve better understanding, and thus, better ability to predict the future. Predictions are further complicated by the inherent uncertainty in how much fossil fuel will be burned worldwide.

In spite of this, there is a general scientific consensus that increasing CO_2 concentrations may cause changes in climate. It is the timing, magnitude, regional variation, and cost or benefits that we cannot yet predict. We must know a great deal more. Our approach to the problem is to select the highest priority research topics for funding: the details of the global carbon cycle, the effect of CO_2 on the climate, and the effects of CO_2 on the growth of vegetation. I will leave the details of our program to Mr. Koomanoff.

As you are aware, we are not the only agency involved in the research on CO_2, or is the U.S. the only nation. Our research is coordinated by the National Climate Program Office, administered by the National Oceanographic and Atmospheric Administration and by the Interagency Committee on Carbon Dioxide and Climate, which is chaired by DOE. The other agencies involved, in addition to NOAA and DOE, are the National Science Foundation, the Department of Agriculture, the National Aeronautics and Space Administration, the United States Geological Survey, the State Department, the Environmental Protection Agency, and the National Bureau of Standards.

There is also a great deal of international interest and activity in CO_2. We have active interaction with the European Community, Canada, and Japan.

The Administration recognizes the importance of the CO_2 issue. We are firmly committed to a balanced program that will answer the associated critical questions. Our request for FY 1983 is $8 million. With this amount, we are convinced that we can plan and continue a program of research that will answer the fundamental questions in a timely way. I believe that this amount is a satisfactory compromise between the clear need at this time to reduce Federal expenditures and the unquestioned importance of the CO_2 problem. We plan to use the larger FY 1982 funding to bring some of the less central research to a timely and cost effective conclusion, and to concentrate our FY 1983 effort on the most essential components.

This concludes my overview. I will be pleased to answer your questions now, or if you prefer, after Mr. Koomanoff has made his presentation.

Mr. **Gore**. I take it what you are saying is that you are going to do a better job with less money and fewer resources.

Dr. **Kane**. We are going to do slightly different things. I think Dr. Koomanoff will tell you the areas we have decided are less important—life in the Government today is a matter of priorities, as you certainly know, and we have decided that some things are more important than others.

Mr. **Gore**. And you think this should receive a lower priority in light of the new evidence that has come out in the last 6 months?

Dr. **Kane**. I think some of the things we were doing should receive less priority, but not the central core of trying to get better understanding.

Mr. **Gore**. What about your research advisory board? Why did you ignore their recommendations?

Dr. **Kane**. Actually, you certainly know the budget process. I believe that their fiscal year 1982 recommendations came out in November, and by that time our fiscal year 1983 budget was, well, probably in your hands by November, almost, or shortly thereafter.

Mr. **Gore**. So the research advisory board is simply irrelevant to your budgetary decisions?

Dr. **Kane**. Not at all. The ERAB report addressed fiscal year 1982 not 1983 budget. I believe the official findings that they came out with, where they established their lists of fiscal year 1982 priorities, was in November.

Mr. **Gore**. That is correct. November of 1981.

Dr. **Kane**. No, 1982. [Laughter.]

I stand corrected, 1981, for the fiscal year 1982 budget.

Mr. **Gore**. I was going to argue that point with you.

Dr. **Kane**. 1981. Excuse me. You had me confused by your hard question. 1981, yes.

Mr. **Gore**. Well, now, let me get it straight. Do you agree that the effort to understand and explain the greenhouse effect and its consequences should be assigned a higher priority?

Dr. **Kane**. I say that, within our budget, we have assigned it the highest priority.

Mr. **Gore**. All right. Now, you have assigned it the highest priority, yet you have cut the request for funding by a third. Isn't that inconsistent?

Dr. **Kane**. I think you would have to look at what we stopped doing, and you would also have to look at the overall priorities and the overall funding stringencies of the whole Department of Energy.

Mr. **Gore**. But my question is, if you agree with your research advisory board and the distinguished scientists that you complimented a moment ago that this problem ought to be given a higher priority, then isn't it inconsistent to take that point of view and then simultaneously diminish the amount of time and attention and resources and people that you devote to this problem?

Dr. **Kane**. Advisory boards are meant to be listened to. We listen to them because we respect their viewpoints, and certainly in the preparation of next year's budget we will take what they said into very serious consideration. However, they do not have the very difficult job of dividing up the money. They recommend priorities, often, but they do not have the job of assigning money.

Mr. GORE. Well, I am talking about your point of view. You told us your point of view was that this problem deserves a higher priority. Isn't it inconsistent, if you believe that, to cut by a third the attention that we are paying to this problem?

Dr. KANE. I don't believe I said this problem deserves higher priority in just those words.

Mr. GORE. Well, do you believe it deserves a lower priority?

Dr. KANE. I think the overall program, in context of the budget that we had to present, shows that we cut out parts of the program that can wait until we are more sure of the central core of our understanding.

Mr. GORE. Well, now, was it the new measurements of the ice melting or the sea level rising or the temperature rising that convinced you it should now receive a lower priority than in the past?

Dr. KANE. The type of work you are talking about there is the very type of work that, Mr. Koomanoff's program, you will see is not receiving lower priority.

Let me give you an example.

Mr. GORE. Well, I have had a lot of examples from a lot of different agencies about how we are going to do a better job with less resources and less time and less personnel, and it has not worked out that way yet. The magic has not kicked in and I doubt very seriously that it will in the greenhouse effect program.

I mean, the consequences of this, if they are real—are devastating. It just makes commonsense, for the people to expect that their Government devote an appropriate amount of attention to finding out the answers to these questions.

To trade that off, as you have, against these other considerations I think is pretty shortsighted. I really do. But we will explore it later. My cochairman here has been very kind in allowing me to pursue these questions now.

Mr. SCHEUER. Well, you are very kind, Mr. Chairman. I think you covered the territory very eloquently, and I have very little more to ask.

Dr. Kane did say, and it puzzled me, that we can afford to wait until we have this central core of knowledge by which we are trying to get a better understanding. Isn't that more or less what you said?

Dr. KANE. Yes; more or less.

Mr. SCHEUER. All right. So getting that central core of knowledge is what is going to trigger an action program of some kind. If you listened to the distinguished first witness this morning, Dr. Calvin, an absolute change in our public policy for this country in energy production, and, hopefully, a change in China and Russia, in the way we organize ourselves in energy production.

Now, you are saying that we can afford to wait until we have this central core of knowledge, of understanding? It is that central core of knowledge and understanding that is going to trigger all kinds of decisionmaking. It seems to me that this basic knowledge base is exactly what we cannot afford to wait for because the absence of that is what is holding up the decisionmaking process on a whole raft of public policy questions on which we have to bite the bullet. But we cannot responsibly go ahead until we have this knowledge base, so how can you tell us we can afford to wait for the knowledge base?

Dr. KANE. I tried not to say that. The things we cut out in reducing our budge —were not this central knowledge base.

Mr. SCHEUER. Well, now, here is a table of priorities, R. & D. priorities, that has been provided by the Research Advisory Board of the Department of Energy. Now, they reported to you over a year ago, they listed 14 levels of priority for all of the various scientific investigations that they were making. Material sciences was an area they asked the most, and climate and carbon dioxide research was second.

So they apparently placed it right at the pinnacle of their concerns.

Dr. KANE. Yes, indeed.

Mr. SCHEUER. If you place that at the pinnacle of your concerns, why would you be cutting the appropriation by a third and cutting our authorization of $17 million by approximately half. Dr. Calvin tells us that we ought to double and triple the present level of effort, the order of magnitude of our effort, to achieve this knowledge base on this extraordinarily complicated subject that involves both national and international decisionmaking. They are recommending more than the $16.7 million. They recommend that to be increased, Dr. Calvin has said we ought to double or triple it, and we are still talking about $50 or $60 million which, in terms of the awesome problem that is being generated by these primeval forces at work that are increasing our temperature, even a quadrupling to $60 or $70 million would be minuscule compared to the awesome consequences of doing nothing and of letting this process escalate to the point where it becomes difficult or impossible to change.

It seems to me that on any intelligent risk-benefit analysis between doing a modest amount of research now and letting these awesome forces escalate and travel up that exponential curve—maybe it is not as exponential as we fear it is; you may be right there; maybe it is a little bit less exponential. But apparently, we are going to get there, and apparently the human and financial costs are going to be almost beyond imagining. How can any rational government say that this knowledge base, which your own advisory council says should be increased, which you have heard Professor Calvin say should be tripled or quadrupled, how can you rationally advise the Congress to cut it by a third?

Dr. KANE. Well, you are asking me several very difficult questions. One, of course, how does an agency makes its decisions? It uses the advice of advisory boards as part of that process, but certainly we do not turn over our responsibility for making decisions to advisory boards.

Mr. SCHEUER. Well, who else do you get advice from?

Dr. KANE. We get it from as many sources as we can, including internal tradeoffs of other budgetary items. That is standard procedure.

Now, getting to the second thing you asked me, the $50 to $60 million budget. I asked Mr. Koomanoff a question that I ask quite often when I am told we should have more research in an area. I asked him a simple question: What is your proposal pressure?

What that means is, how many people with smart ideas are coming to you and asking for money? That is an important question.

I have spent many years administering research, and there is a rule of thumb: If you are not turning down roughly half the proposals, you receive, you are probably supporting poor work. It turns out Mr. Koomanoff is not turning down a lot. I think your idea of keeping it to core research and expanding it to $50 or $60 million is totally unrealistic. I do not think there are that many people that can manipulate big models, for instance.

I could be wrong, and you may want to question the other witnesses on that. But I guess I will come back to the viewpoint that in a very difficult budget year we made some hard decisions, and we are trying to explain to you the basis on which those decisions were made. We do not expect you always to agree with them.

Mr. Gore. Mr. Chairman, if I may note for the record that your predecessor, Mr. Kane, a Mr. Pewitt, stated to these two subcommittees last July that in the face of these difficult budget pressures, he agreed that this problem was so challenging that he was going to recommend, and expected to see, an increase in the funding for the carbon dioxide program.

Now, that statement has gone by the wayside, and I have to believe that you are under the same pressures from OMB that your predecessor was, and I don't want us to be unfair to you this morning because it puts you in a tough spot to make sense out of irrational actions on the part of others, if that is the case, so we don't want to put you in that spot if it is unfair to do so, and you don't have to speak up and say that you appreciate that, because I know it puts you in a tough spot.

Why don't we go ahead and hear from Mr. Koomanoff?

STATEMENT OF FREDERICK A. KOOMANOFF, DIRECTOR, CARBON DIOXIDE RESEARCH DIVISION, DEPARTMENT OF ENERGY

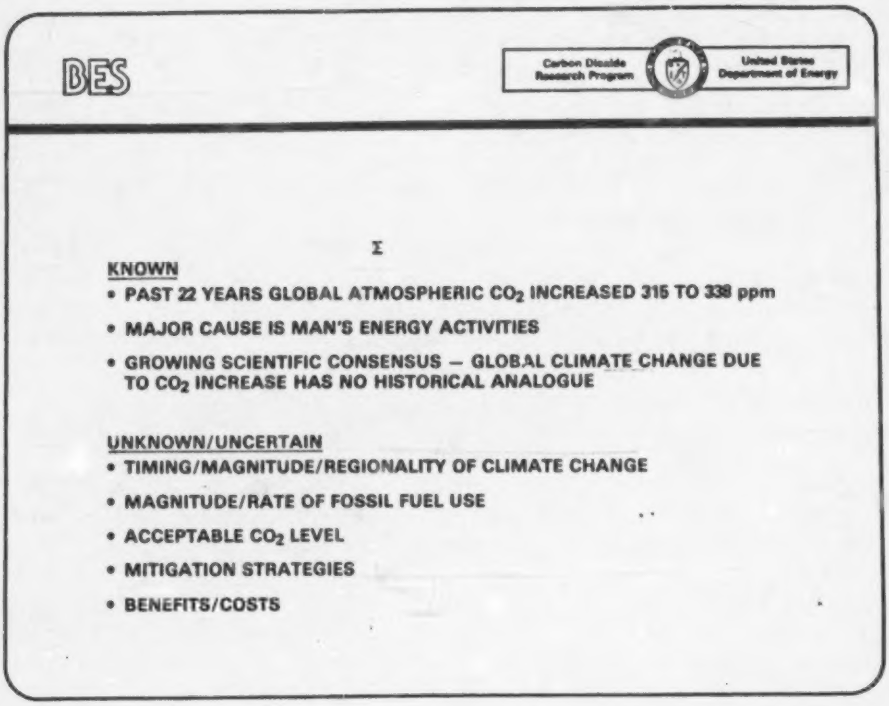
Mr. Koomanoff. Thank you.

When I was here last July just taking over the directorship of the Carbon Dioxide Research Division, you asked if I would come back and report to you as to what our program would be and where we would be going.

In order to do this, the first step was to find out what we know, what we don't know, what is uncertain; in some cases, what is known, and the timeframe for obtaining information.

Accordingly, I would like to use a few Vu-Graphs as a way of describing our program and what we found.

[Slide 1 shown.]



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Carbon Dioxide Research Program

United States Department of Energy

Σ

KNOWN

- PAST 22 YEARS GLOBAL ATMOSPHERIC CO_2 INCREASED 315 TO 338 ppm
- MAJOR CAUSE IS MAN'S ENERGY ACTIVITIES
- GROWING SCIENTIFIC CONSENSUS – GLOBAL CLIMATE CHANGE DUE TO CO_2 INCREASE HAS NO HISTORICAL ANALOGUE

UNKNOWN/UNCERTAIN

- TIMING/MAGNITUDE/REGIONALITY OF CLIMATE CHANGE
- MAGNITUDE/RATE OF FOSSIL FUEL USE
- ACCEPTABLE CO_2 LEVEL
- MITIGATION STRATEGIES
- BENEFITS/COSTS

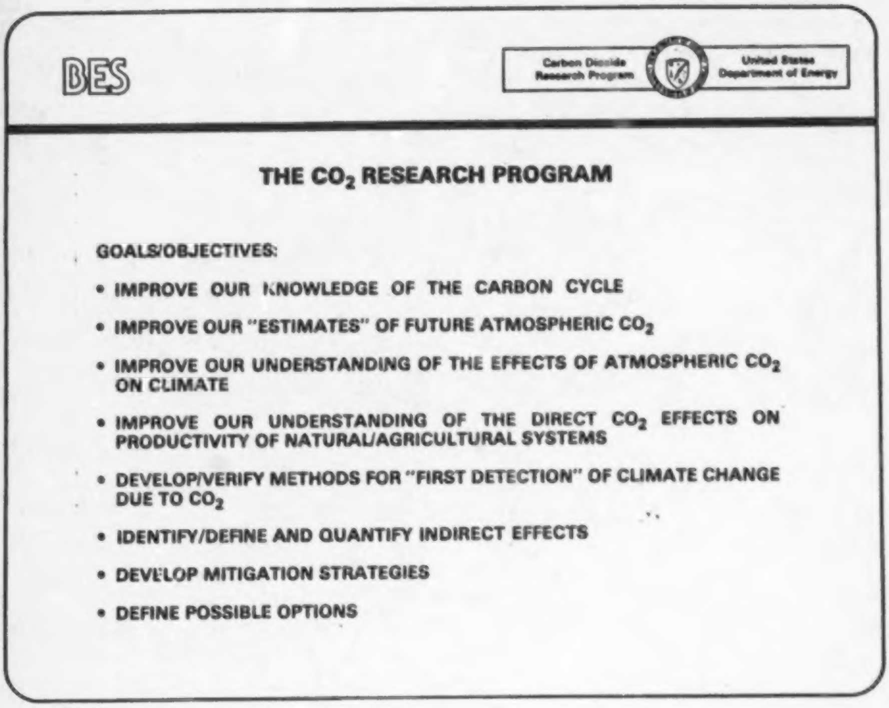
SLIDE 1

Mr. KOOMANOFF. First, an overview summary of what is known. We know explicitly that for the past 22 years, global atmospheric carbon dioxide has increased. We know, too, that the major cause of it is man's energy activities.

We also know that there is a growing scientific consensus that the global climate change due to carbon dioxide increase has no historical analog. We are cognizant of the concern and the problem.

However, when we look at what is unknown and uncertain just in summary, the timing, the magnitude, the regionality of climate change are unknown. The magnitude and rate of fossil fuel use 50, 100 years in the future. What is an acceptable level of carbon dioxide? What mitigation or control strategies exist? What are benefits and costs?

[Slide 2 shown.]



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Carbon Dioxide
Research Program

United States
Department of Energy

THE CO_2 RESEARCH PROGRAM

GOALS/OBJECTIVES:

- IMPROVE OUR KNOWLEDGE OF THE CARBON CYCLE
- IMPROVE OUR "ESTIMATES" OF FUTURE ATMOSPHERIC CO_2
- IMPROVE OUR UNDERSTANDING OF THE EFFECTS OF ATMOSPHERIC CO_2 ON CLIMATE
- IMPROVE OUR UNDERSTANDING OF THE DIRECT CO_2 EFFECTS ON PRODUCTIVITY OF NATURAL/AGRICULTURAL SYSTEMS
- DEVELOP/VERIFY METHODS FOR "FIRST DETECTION" OF CLIMATE CHANGE DUE TO CO_2
- IDENTIFY/DEFINE AND QUANTIFY INDIRECT EFFECTS
- DEVELOP MITIGATION STRATEGIES
- DEFINE POSSIBLE OPTIONS

SLIDE 2

Mr. KOOMANOFF. Now, I would like to discuss our research objectives.

In order to do our job, we have to improve our knowledge of the carbon cycle, the sources and sinks, and I will get into this in a little more detail later. We have to improve our estimates of future atmospheric carbon dioxide because, then and only then can we tell how many parts per million we will have at some time in the future, and then we can estimate when something will happen.

We have to improve our understanding of the direct effects of atmospheric carbon dioxide on climate, especially regionality and seasonality. We have to improve our understanding of the direct effects of carbon dioxide on the productivity of natural and agricultural systems, and a key issue that was discussed over and over, we have to develop and verify methods for first detection of climate change due to carbon dioxide.

Mr. SCHEUER. Can I interrupt you, Mr. Koomanoff? You are laying out a very intelligent and thoughtful research program.

Mr. KOOMANOFF. Thank you.

Mr. SCHEUER. It is very impressive. It sums up most of what we have heard this morning from the very expert and thoughtful witnesses we have heard. You don't seem to be in disagreement with them at all.

My question to you is, you can't beat somebody with nobody, and you can't accomplish something with nothing. If you take these research goals as a given, and it would be hard to quarrel with them—I would embrace them—how can you justify a one-third reduction in the research budget that was appropriated and a 50 percent reduction from the research budget that was authorized?

You are describing very well, you are summarizing very well, the testimony we have heard all day and the need for a very comprehensive and thoughtful research program. If that is true, how can you possibly justify the kind of reductions in funding for this program that your agency is asking us for?

Dr. KANE. Mr. Chairman——

Mr. SCHEUER. Excuse me. I would like to hear from Mr. Koomanoff.

Mr. KOOMANOFF. We went back and looked at some of the research projects that we had done before. There are certain aspects of research that one has to take into consideration when he looks at budgets. You have to realize I took over as of August 1981, just about 7 months ago.

If you go back into the 1981 budget, you will find that we expended $2 million in the transient tracer ocean program to find out about deep mixing in the ocean using tritium and other tracers that were available. That program started in 1977, just to start the planning. It was 1981 before we got the boats into the ocean and at the 200-plus sites to take the samples. We shared this research activity with National Science Foundation; we each put in $2 million.

In 1982, to continue that program, we are putting in half a million dollars only. The reason for that is that the boats now are in; the data has to be analyzed. In 1983, we will again probably be putting in half a million dollars for analysis. Then that project will basically, as far as the North Atlantic part of the program, be over. That data will be used in some of our modeling activities.

We did some research, too, on developing of new instrumentation—lasers, for example—to find out about argon 39, another tracer. That instrument will be developed by the end of this year. We don't have to build another instrument next year. It will be there and it can be used and will be used, but the cost for development compared to the cost for use is quite different.

We did some studies of economics in the agricultural field to construct models for determining if we could really see what the effects of climate change on agriculture and found that the models needed regional data very clearly; otherwise, we were playing if we were trying to get answers.

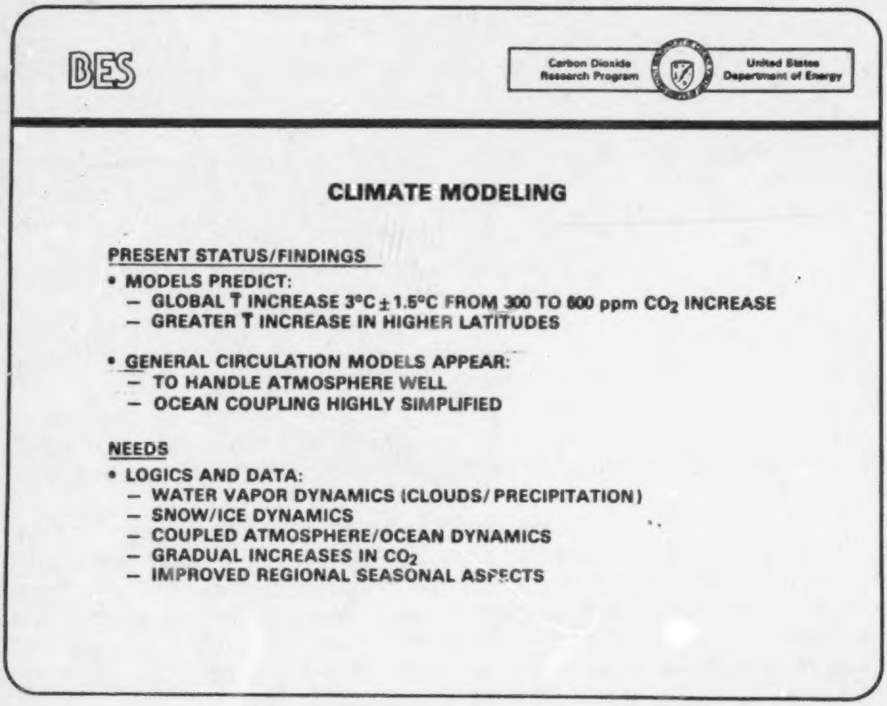
We are not doing that work any more. There are certain phases of the work that is coming in and out. We are working much more closely with our other sister agencies on some of this. In the future we may be coming back and asking you for some more money.

If I were continuing, one of the things in the climate model I would be showing if the Vu-Graphs on our findings and our nonfindings under climate modeling. I think this becomes a key issue because it reinforces some of the things that we have to do when we plan. We are not always going to have a monotonic curve on budgets.

Mr. SCHEUER. You are not going to have what?

Mr. KOOMANOFF. A one-directional curve. It is going to go up and down on a cyclical basis.

[Slide 3 shown.]



BES

Carbon Dioxide
Research Program

United States
Department of Energy

CLIMATE MODELING

PRESENT STATUS/FINDINGS
- MODELS PREDICT:
  - GLOBAL $\bar{T}$ INCREASE 3°C ± 1.5°C FROM 300 TO 600 ppm CO_2 INCREASE
  - GREATER $\bar{T}$ INCREASE IN HIGHER LATITUDES
- GENERAL CIRCULATION MODELS APPEAR:
  - TO HANDLE ATMOSPHERE WELL
  - OCEAN COUPLING HIGHLY SIMPLIFIED

NEEDS
- LOGICS AND DATA:
  - WATER VAPOR DYNAMICS (CLOUDS/PRECIPITATION)
  - SNOW/ICE DYNAMICS
  - COUPLED ATMOSPHERE/OCEAN DYNAMICS
  - GRADUAL INCREASES IN CO_2
  - IMPROVED REGIONAL SEASONAL ASPECTS

SLIDE 3

Mr. KOOMANOFF. Our needs in modeling—right now we know how to handle the atmospheric aspects of climate modeling. The oceans are handled very poorly. We are just getting that data. We will not have that data until 1983 or 1984 to start putting into models, and that, included with other data, will then help give us at least two data points by which to improve our models.

We must know more about clouds. One of the key issues to make climate models useful, especially for regionality and seasonality, is clouds. In 1983, there is going to be a program in satellite monitoring of clouds and their radiative properties. That program is not a DOE carbon dioxide program, but we will be working with those people through our interagency committee on carbon dioxide and climate to make sure that the data they get will be able to feed into our models. It will be about 5 years before that data set is complete, but we will be getting information all along and trying to improve our models.

Mr. SCHEUER. Is that work being done by NOAA?

Mr. RICHES. It is an international effort, and it includes NOAA, NASA, and other satellites of opportunity. In fact, Dr. Hansen referred to it in his testimony.

Mr. SCHEUER. And you say that is being adequately funded beyond the perimeters of your R&D budget.

Mr. KOOMANOFF. Sir, I cannot answer that. I cannot tell you whether that program is or is not being adequately funded. I just do not know. I would hope that that program is being adequately funded. Sometimes DOE can add a little money to a program. For instance, we could not afford $4 million for boats to go out in transient tracing operations but, working with the National Science Foundation, we had a beautiful partner and we were able to work that way, and we have done that on many projects.

Three years ago, if you were to ask people about biosphere carbon contribution to atmospheric we would be talking about plus or minus 5 gigatons. We are now talking about plus 1 or minus gigatons, we are reducing our uncertainty.

We did studies on land management as to forest practices to see if that affected the balance of carbon. We don't have to do those studies any more because we found out that while they were interesting and they were good studies, they were marginal in relationship to the total numbers that we are talking about.

So yes, there are some things that we are doing, that we did do in the past, that we are cutting out. There are some things that we will be continuing. Some of our projects are 2-year projects; they are not just 1-year projects.

Mr. **Scheuer**. When your advisory council recommended an increase from the $16.7 million level, they were not privy to this information. Much of this work was coming to an end or at least the expensive portion of the research was nearing completion. Were other major programmatic aspects of your research being funded by other agencies? Was this council not aware that they recommended an increase above the $16.7 million?

Dr. **Kane**. I cannot answer that.

Mr. **Koomanoff**. I did not work with the ERAB panels.

Dr. **Kane**. Would you like me to find out for you?

Mr. **Scheuer**. I think that would be helpful to us if you would submit that.

Dr. **Kane**. I will, indeed.

Mr. **Scheuer**. We will hold the record open for you.

[The information follows:]

ENERGY RESEARCH ADVISORY BOARD RECOMMENDATION—CARBON DIOXIDE RESEARCH

Energy Research Advisory Board (ERAB) recommendations on Federal Energy research and development priorities were based, in part, on a thorough review of the Department's fiscal year 1982 Budget Request to Congress. That budget clearly states that some carbon dioxide and climate research projects will be completed in fiscal year 1981 and fiscal year 1982; that DOE has the lead responsibility for the comprehensive Federal research program; and is part of the National Climate Program. Recognizing these facts, the ERAB members were in strong agreement on the importance of this program, and recommended an increased DOE effort.

Mr. **Scheuer**. Before you go ahead, I would like to ask Dr. Kane, if, the National Advisory Council had significant input into the decision on funding levels this year.

Dr. **Kane**. I think that is fair to say, that this year they had no effect.

Mr. **Scheuer**. Will they have more or considerable input next year?

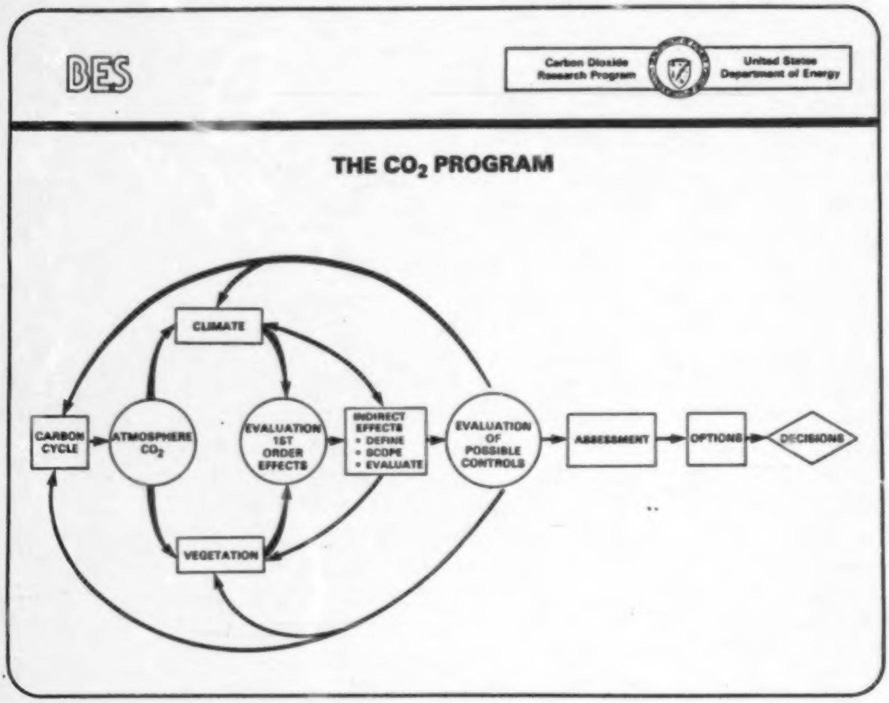
Dr. **Kane**. I cannot give you a positive answer. My conclusion, drawn from the kind of credibility that this board is getting, is yes, they will. That is a personal inference that I draw from lots of observations. Nobody has told me, we are going to give the board more credence next year. I believe that they are gaining credibility, and as I say, they will be factored into the decision process more heavily next year.

Mr. **Scheuer**. Well, if Dr. Calvin is a fair example of the quality of the National Advisory Council, it seems to us that you would be extraordinarily well advised to take what they have to say very seriously.

Mr. Koomanoff, please proceed.

Mr. **Koomanoff**. Could I have the next slide, Mike, please.

[Slide 4 shown.]



BES

Carbon Dioxide Research Program

United States Department of Energy

THE CO_2 PROGRAM

CARBON CYCLE

ATMOSPHERE CO_2

CLIMATE

VEGETATION

EVALUATION 1ST ORDER EFFECTS

INDIRECT EFFECTS
- DEFINE
- SCOPE
- EVALUATE

EVALUATION OF POSSIBLE CONTROLS

ASSESSMENT

OPTIONS

DECISIONS

Slide 4

Mr. **Koomanoff**. I would like to try to show you schematically the logic of how we are trying to put the program together. We look at carbon cycle first because that is our key issue. Without knowing how the carbon cycle works, we cannot know what the atmospheric level is or will be. Once we know the atmospheric level, then we can start studying the effects on climate and vegetation. Then we have to evaluate what we call these first-order effects. They let us look at our indirect effects. There are feedbacks then, we can evaluate possible controls, we can do our assessment, then present options so that finally a decision can be made.

We are concentrating at this point in time on the data collection and analysis portion of our program. That does not mean we are not doing work in indirect or in mitigation strategies, but we are concentrating.

In the carbon cycle, we know the atmospheric carbon dioxide is increasing. The fossil emissions are well known. We assume that 5 to 10 percent is taken up by the biosphere; 40 percent is absorbed by the oceans. However, our uncertainty issues are great. Our carbon dioxide budgets still don't balance, but we have brought them down in the last year and a half.

We have to know more about the magnitude of deforestation. We have a computer map that we have just produced which shows 37 different types of vegetational species or ecosystems across the world. It is the first time it has been developed to this level. We now have an inventory. This is being published, and being reviewed by the scientific community.

We are also working on satellite data from 1972, when it first started, because then we will be able to see the changes that have occurred so we just do not have a one-point inventory but we can see what the changes have been and get some good information on deforestation.

Ocean mixing I have already discussed.

Climate modeling we already discussed.

The vegetation response to carbon dioxide became one of the key issues that, when I took over this program, I felt was very important about. Carbon dioxide is an essential nutrient. We have to know more about this. We doubled our budget between 1981 and 1982 in this area. Some of that, however, cannot all be spent in 1 year. Some of it is 2-year money because that is the only way you can get the practical approach to the research.

We have to know the biochemical limits of carbon dioxide fixation—how much can the plants take—the physiology of the carbon storage and yields, the carbon dioxide, and water use efficiency. Some plants with increased carbon dioxide may use less water; and we have possible genetic adaptions.

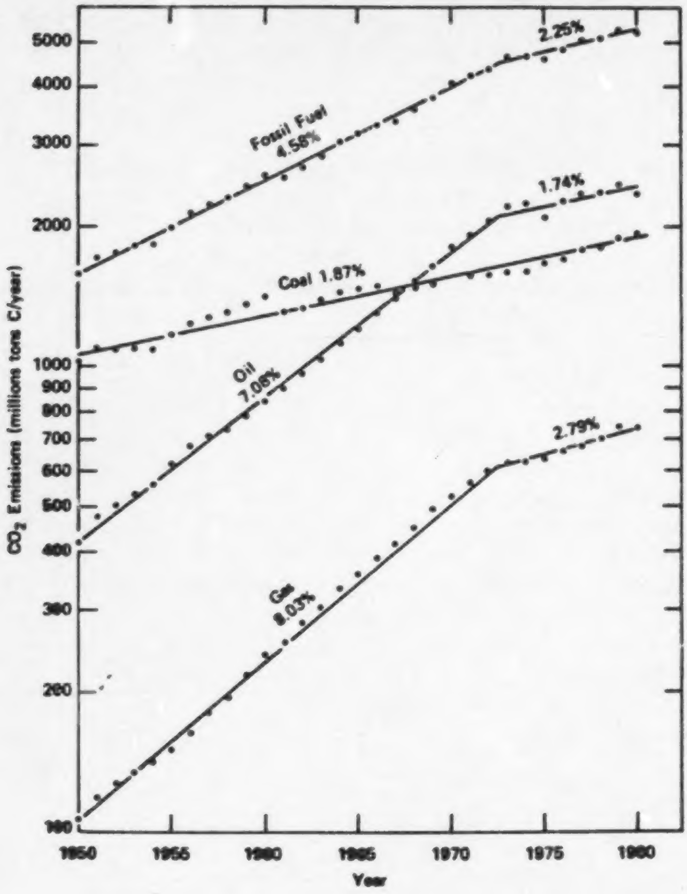
Last year, you asked me about the AAAS and if we were going to support any of their work. We are supporting a major conference, an international conference, on this whole of vegetation response to carbon dioxide, that will be held in May in Athens, Ga. It will be a total international meeting. But even more so, we have three of our other sister agencies supporting it with us. The sister agencies supporting DOE; are the National Science Foundation; the Department of Agriculture; and EPA. Even the National Academy of Sciences, under Bill Nierenberg is doing an assessment for the Congress on the carbon dioxide cycle.

We are starting to find out about carbon dioxide not in just the lab, but we are developing test mechanisms which are verifiable to bring it out into the field, into the real world, so that we won't have so much argument about what is theory and what is practice.

So that is one of the key areas that we are really moving on, but you have to go with a plan first. It must be a sensible, peer-reviewed plan so the scientific community understands it and you can get their advice, because we don't have all the smarts.

[Slide 5 shown.]

FOSSIL CO_2 EMISSIONS BY TYPE OF FUEL



Mr. **Koomanoff**. This data was just published. It was done for us by the Institute of Energy Analysis at Oak Ridge by Dr. Rotty, and it shows what has happened with production of fossil fuel data over the last few years.

In 1978, when we first published our report on real fossil fuel emissions, between 1950 and 1973 emissions due to burning gasoline was growing at the rate of 8 percent per annum. It has, from 1973 on, been growing at the rate of 2.8 percent per annum.

Oil was growing at the rate of 7 percent per annum; it is now down to 1.7 percent. Coal has basically remained the same during this entire timeframe, about 1.9 percent. When you sum these all together, our report in 1978, stated that the total fossil fuel emissions were at an annual rate of 4.6 percent. Since 1973, that has dropped now to 2.25 percent.

Mr. **Scheuer**. Yes; but there is still an increase going on.

Mr. **Koomanoff**. Sir, that is my next chart.

Mr. **Scheuer**. And we are still headed up that parabola, are we not? The American people have not ended their love affair with the internal combustion machine.

Mr. **Koomanoff**. And we won't.

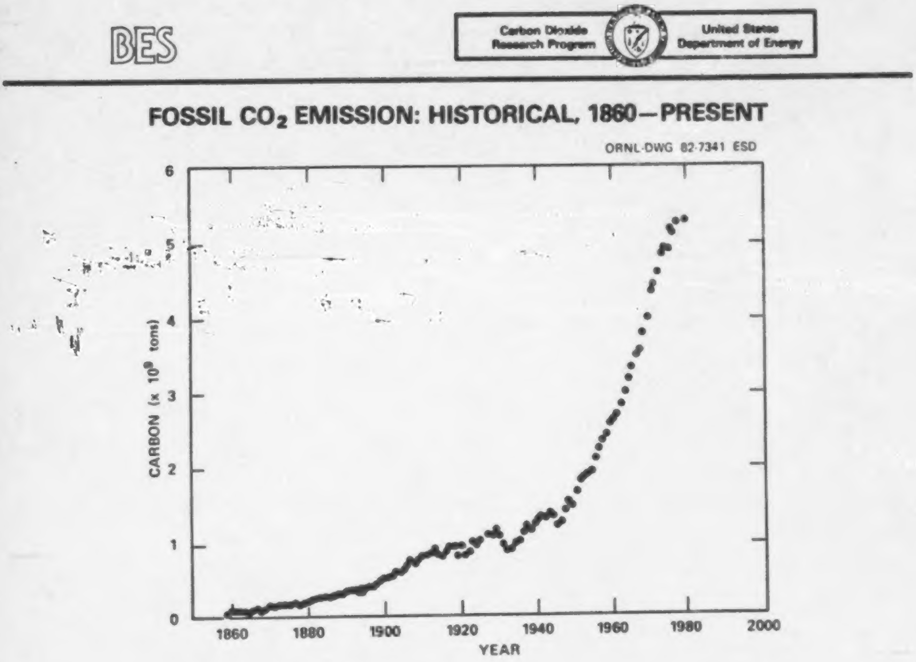
Mr. **Scheuer**. And we won't.

Mr. **Koomanoff**. That is right.

Mr. **Scheuer**. So what we have is an upward scale with a couple of jags in it. You know, two steps forward, one step back. We may have reduced the rate of increase somewhat for some period of time, we know not how long, but there is absolutely no question that the rate of gasoline consumption and the rate of fossil fuel consumption is going up, is it not?

Mr. **Koomanoff**. Next slide, please.

[Slide 6 shown.]



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Carbon Dioxide Research Program

United States Department of Energy

FOSSIL CO$_2$ EMISSION: HISTORICAL, 1860—PRESENT

ORNL-DWG 82-7341 ESD

SLIDE 6

Mr. KOOMANOFF. This shows it right here, sir.

Mr. SCHEUER. Yes.

Mr. KOOMANOFF. This is, in absolute terms, the chart from 1860 through 1980, and it shows the growth with the perturbations for war and depression. It also shows that, even though the rate has decreased, the total amount is still increased, which is a key issue. But what it did show is that we just started to get that little turn. The most up-to-date data that I have for 1981 shows that the plateauing or slighter increase is starting to show up in these data.

So, yes, it takes time when a rate changes before you see it. Now, that does not mean that we are not still putting a lot of carbon dioxide into the atmosphere. We are.

Mr. SCHEUER. At an increasing rate, but at a diminished rate of increase, but nevertheless, an increasing rate.

Mr. KOOMANOFF. Yes, sir, but it is the slope of the curve that counts.

Mr. SCHEUER. That is quite true.

You are still talking about a dramatic increase over a period of a decade or two of consumption and of spewing the carbon dioxide into the air. I get a great sense of urgency from the witnesses that preceded you. I must say, Mr. Koomanoff, you have given us a very impressive and thoughtful presentation of these various research and development missions, extremely impressive and very interesting.

I am hard put to understand by what miracle you are going to accomplish this very impressive, comprehensive research program with a budget that has been cut by one-third. Now, maybe I am looking at it very simplistically, but you have a very impressive mission, and you are requesting one-third less than what we appropriated and only half of what we authorized, and I am hard put to see how you can do that, by mirrors or blue smoke or the pea game or whatever.

It seems to me that it is an inexorable law of nature, when you provide less funding and less personnel and less resources to research programs, you get less research out of the pipeline, not more. That sort of sums up my feeling.

We are running well overtime, and we have imposed on your patience long enough. Let's go off the record.

[Discussion off the record.]

Mr. **SCHEUER**. Go ahead with the conclusion of your testimony.

Mr. **KOOMANOFF**. That's it.

[The prepared statement of Mr. Koomanoff follows:]

STATEMENT OF FREDERICK A. KOOMANOFF
DIRECTOR, CARBON DIOXIDE RESEARCH DIVISION
DEPARTMENT OF ENERGY
BEFORE THE
NATURAL RESOURCES, AGRICULTURAL RESEARCH AND
ENVIRONMENT SUBCOMMITTEE
AND THE
INVESTIGATIONS AND OVERSIGHT SUBCOMMITTEE
HOUSE SCIENCE AND TECHNOLOGY COMMITTEE
MARCH 25, 1982

During the past six months, the Department of Energy has conducted an indepth review of the CO_2 research program. What is now known, what is still unknown, and what is uncertain has been identified. These findings have been shared with other government agencies, through the Interagency Committee on CO_2 and Climate of the National Climate Program Office which Dr. Trivelpiece described. Based upon this review, the CO_2 research program has become more focused on research that will produce hard scientific data. Table 1 summarizes the principal issues that are known and those that are unknown.

TABLE 1

KNOWN

o In the past 22 years, global atmospheric CO_2 has increased from 315 to 338 parts per million.

o The major cause of the increase is man's energy activities.

o There is a scientific consensus that the global climate change due to CO_2 increase has no historical analogue.

UNKNOWN/UNCERTAIN

o The timing, magnitude, and regionality of climate change.

- The future consumption of fossil fuels.
- The level of CO_2 that is acceptable in terms of minimum impact.
- Possible mitigation strategies.
- The costs and benefits of higher CO_2 concentrations.

The message inherent in this summary is that the uncertainties and unknowns must be reduced before it is possible to make prudent decisions. We must improve our understanding of the fundamental relationships between CO_2 concentration and climate, increase data collection, improve measurements, and develop reliable models. We can then answer specific questions about the sources and sinks of carbon dioxide, the magnitude of climate change and other possible effects with greater confidence. A means by which to detect and verify the cause-effect relationships of CO_2-climate and a better understanding of the response of vegetation must also be developed.

Figure 1 shows the CO_2 research program logic.

The DOE program focuses primarily on three principal areas that require more research before the above CO_2-climate related questions can be answered. These three areas are the global carbon cycle, climate effects, and vegetation effects.

(1) Prediction of future atmospheric CO_2 concentration requires additional information on the sources and sinks of CO_2. Simply

put, where does it come from and what components of the biogeochemical system absorb it? Present day emissions from the burning of fossil fuels can be estimated to an acceptable accuracy. Estimates of CO_2 releases from other sources, such as the oxidation of forest materials, are much less certain. Similarly, our scientific understanding of the behavior of the various sinks, such as the uptake of CO_2 by the ocean, its transfer to the deep oceans and the fundamental CO_2 fixing actions of the biosphere, requires improvement so that more accurate models may be developed to aid in predicting future levels of atmospheric CO_2.

(2) Research efforts include an attempt to predict regional and global changes in temperature and precipitation. These efforts are also aimed at identifying climate changes resulting directly from the effects of CO_2 as differentiated from the many other factors that could have been involved. Research with general circulation models is aimed at understanding how atmospheric CO_2-induced climate change may relate to the nonatmospheric components of the climate system such as oceans, land and the cryosphere. These relationships are not yet well understood or modeled. For example, preliminary results from a study now underway suggest that the ocean does not respond immediately to an increase in the temperature of the atmosphere. A delay of a decade or more may result from the ocean's thermal inertia.

It may never be possible to attribute a climate change directly to an increase in atmospheric CO_2. It is important, however, to explore methods for detecting the small changes which some models predict would be caused by CO_2 amidst variations in climate due to other factors. Currently, temperature changes predicted by general circulation models cannot be identified unambiguously because the natural year-to-year variability (over the entire 100 year record) of the global average temperature ($\pm$0.4 degrees C) is greater than that expected from the approximately 14% increase in CO_2 since the turn of the century. Research aimed at detecting a change in climate will enable us to test the atmospheric models by comparing the predicted effects with those measured.

(3) Increased atmospheric CO_2 may benefit vegetation and crops because it is an essential ingredient for plant growth. More CO_2 may increase crop yield and result in greater storage of carbon by forests, for example. Research is being done on the photosynthetic process, as well as the physiology and water use of plants to provide a basis for predicting vegetation response to rising atmospheric CO_2. Such a beneficial effect of CO_2 would occur independent of postulated CO_2-induced climate change.

In addition, we are identifying and defining possible indirect CO_2-climate induced effects such as temperature and circulation effects (e.g., effect on the West Antarctic ice sheet, fisheries and hydrologic perturbations which could affect water availability).

Our research and analysis activities are rapidly improving our understanding. For example, careful analysis of data on fossil fuel consumption shows that in 1981 releases were 5.3 GT (gigaton = 1 billion metric tons) of carbon to the atmosphere as CO_2. The growth rate of carbon emissions, which averaged over 4.5 percent per year throughout the third quarter of this century, has dropped to less than 2.5 percent per year since 1973. Most studies of the CO_2 question have assumed future growth rates closer to the earlier, higher number. The best current energy forecasts, however, suggest that growth rates for carbon releases over the next 30 to 50 years will most likely average 2.0 percent per year or less. An upper limit of 3 percent per year and a lower limit of 1 percent per year now seem plausible as a basis for future estimates.

Land use changes (forest clearing, burning, abandonment of farmland, etc.) throughout the world in 1980 led to a net release of less CO_2 than did fossil fuel burning. The best current estimates suggest a release of about 2 GT carbon per year. Due to a variety of uncertainties, however, it remains possible that changing land use practices actually result in a current net release to the atmosphere of anything from +5 to -1 GT carbon per year. There is general agreement, however, that land use changes will not produce a significant fraction of man's total future releases of CO_2. If there is to be a future carbon dioxide problem, it will be dominated by the burning of fossil fuels, not the burning of forests.

The combined result of these revisions of source data is to decrease significantly recent estimates of the rate at which future atmospheric CO_2 concentrations are predicted to rise. Many earlier studies of the CO_2 question quoted a "doubling time" -- the number of years before CO_2 concentrations reach 600 parts per million, about twice the preindustrial level -- of about 50 years. Using identical logic, but substituting the revised data, the most likely doubling time is almost twice as far away, close to 100 years from now. While this is comforting, it does not make our research programs less urgent. We do not know what is an acceptable CO_2 level, in terms of an acceptable impact.

This analysis clearly shows the value of and need for obtaining better understanding through research. Continual research is mandatory to ensure a sound quantitative knowledge base to aid in decision making. The major fraction of our effort will continue to be in understanding the complex physics, chemistry, and biology problems that are fundamental to the question of CO_2-climate. It is only through the deeper insight that we will be able to develop prediction models capable of producing improved estimates of possible regional and seasonal climate changes.

In summary, the CO_2 issue is one of great complexity and difficulty. We are focusing the research on the question of greatest importance--better understanding of the science involved.

BES

Carbon Dioxide Research Program

United States Department of Energy

THE CO$_2$ PROGRAM

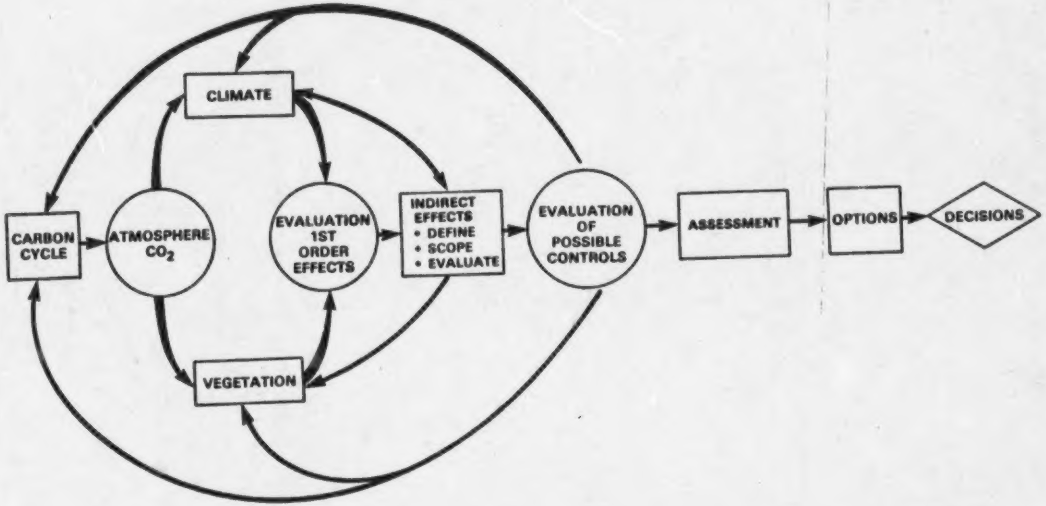
CARBON CYCLE
ATMOSPHERE CO$_2$
CLIMATE
VEGETATION
EVALUATION 1ST ORDER EFFECTS
INDIRECT EFFECTS
• DEFINE
• SCOPE
• EVALUATE
EVALUATION OF POSSIBLE CONTROLS
ASSESSMENT
OPTIONS
DECISIONS

Figure 1

Mr. **Scheuer**. I must say, you have given us very impressive testimony, both of you. You are obviously professional and knowledgeable people, and you have given us an impressive program.

I understand that in some areas of life, less is more, but I just have not come to that point in comprehension that less is more in this extraordinarily important research mission that you have.

Mr. **Koomanoff**. On the wall, we show one of the projects that we have going on. Now, this is a way where we try to multiply our dollars at DOE. One of the issues is that everyone says we only have one excellent data set of Keeling's from 1957 to today. What happened in the past?

At Pacific Northwest Laboratory, at our observatory there, the idea that from the spectral plates that were taken at many observatories, we should be able to, knowing the intensity of light and the wave length, to mathematically calculate the amount of carbon dioxide in the atmosphere at that time.

They have developed a mathematical method by which to calculate past CO_2 levels. But first The spectral plates had to be found.

In 1925, at Mount Haiqua Halu, Ariz., that observatory that you see in the little picture up on top was abandoned. About a year and a half ago, we went to that abandoned observatory and, in the root cellar, found 250 of these plates, with rattlesnakes, too.

We have over 1,000 spectras, because many times each plate has three to five spectras. Then, working with NOAA, because they have a camera—so we did not have to go buy a camera or rent it—we could reduce the plates into picture slide.

Then, working with NASA, because they had the equipment, we were able to digitize that data by the end of this year, we will have CO_2 level data points, one data point in the 1890 timeframe and quite a few in the 1920's.

Further as to trace gases, that Dr. Hansen mentioned; this technique can be used for trace gases. We did not even know that when we first started, and we are having a seminar in about 1 week or 2, within basic energy sciences, mathematics, and computer sciences group to start taking advantage of this new technique.

This is one example of trying ways of increasing our productivity. Some will work and some will fail, but we are trying.

Mr. **Scheuer**. Well, you are obviously a very credible professional witness, and I appreciate the insights that you have given us. You are proceeding down numerous research paths.

Can you give us a timetable as to when you would have the totality of this research synthesized and completed so that public policy recommendations on changes in our national balance of energy production, the kind of really tough public policy decisions that we are going to have to make that have been discussed by the prior witnesses? When do you think you are going to have that research base that will be adequate for the kind of decisions we are going to make in Congress?

Mr. **Koomanoff**. Presently, we have out in peer review, within the Department of Energy and our sister agencies like NOAA, NSF, and others, plus some of the leading universities, three basic detailed research plans, one on the carbon cycle, one on climate model and first detection, and one on the vegetation effects.

In these plans, we have what we call time lines, which said, if we are doing this research and if these things come out like we hope, we expect to have key information by a specific time.

For example, today there is no question that the sign of the equation, as it were, for increasing carbon dioxide is going to be positive; there is going to be an increase in the global temperature. Right now, we do not know the sign of the regionality and seasonality. We hope to have something like that somewhere, hopefully, in the 1986-1987 timeframe.

These time estimates are in these documents. They are being reviewed, and we are asking our scientific colleagues to come back and say, are we nuts; are we too ambitious? I would hope that you would give me about 2 months. Then, I should have these documents, and I will be glad to send them to your staff so that they could review them, and I would be glad to further answer that.

Mr. **Scheuer**. Would you?

Mr. **Koomanoff**. But to give you a definitive answer until I get feedback from some of my planning from the scientific community, I think, would be premature. We will get back to you in approximately 2 months.

Mr. **Scheuer**. Very good. Well, we will look forward to receiving that data. Now, will that data also be provided to your Energy Research Advisory Board, and will their opinions be solicited?

Mr. **Koomanoff**. Oh, yes, sir.

Mr. **Scheuer**. Very good.

Mr. **Koomanoff**. He is my boss, and he insists on things like that.

Mr. **Scheuer**. Very good.

All right. I thank you both. You have been very patient with us and very forthcoming. We appreciate it, and we will look forward to hearing from you.

With your indulgence, we are going to leave the record open for my colleagues who were not here, and perhaps myself, too, to ask some further questions in writing.

Thank you very, very much. The meeting is adjourned.

[Whereupon, at 12:30 p.m., the subcommittees recessed, to reconvene at the call of the Chair.]

APPENDIX I

QUESTIONS AND ANSWERS SUBMITTED FOR THE RECORD

ANSWERS TO QUESTIONS ASKED OF DR. MELVIN CALVIN

1. CO_2 Research Priority

The Energy Research Advisory Board (ERAB) ranked CO_2 research as the highest priority program in Energy R&D.

A. Would you give us a short history of the Board?

Answer A:

The Energy Research Advisory Board was established on June 19, 1978, and renewed on June 19, 1980. Its purpose is to provide advice to the Secretary, Deputy Secretary, Under Secretary, and Assistant Secretaries as well as the Director, Office of Energy Research, on overall R&D conducted in DOE and to provide long-range guidance in these areas to the Department. Members are selected primarily for technical competence, but careful attention is given to balance among such factors as sex, race, and geographical distribution. Additionally, the Board is divided into a number of panels, subpanels, and study groups which meet on a schedule determined by the reviews they are conducting. The Board is currently working on six studies for DOE and is also continuing its responsibility for reviewing nominations and making recommendations to DOE concerning the Enrico Fermi and E.O. Lawrence Memorial Awards.

Early in 1981, the Energy Research Advisory Board (ERAB) was reconstituted and is now the highest level independent scientific advisory committee serving the Department of Energy, and reports to the Secretary through the Deputy Secretary. (The Office of Energy Research provides administrative support to the Board.)

The Board has provided advice on a wide range of issues since its establishment in 1978. An example of the type of review the Board performed was a study completed late in 1981 on "Federal Energy RD&D Priorities." This study addressed a number of concerns, principal among them the relative merits of each major R&D program supported by DOE, the appropriate Federal role in energy R&D, and the strategic R&D objectives for the near, mid and long term. The Board also recently completed a report on the potential contribution of biomass resources to energy supplies.

During the coming year, the Board plans to complete studies on the role of the multiprogram national laboratories, advanced isotope separation technology, and on DOE's conservation and solar programs. In addition, the Board will continue to conduct studies as requested by the Secretary and Deputy Secretary.

B. What information was considered in placing such a high priority to the CO_2 program?

Answer B:

The Board primarily relied on the broad expertise of its membership in assigning high priority to the CO_2 research program. For instance, several board members have expertise in environmental sciences with a general concern for environmental quality and regulation while others with expertise in fossil energy have concerns about the potential impacts and uncertainties of CO_2 prolems on fossil technology development and utilization. In addition, the Board has been briefed on CO_2 research programs, and reviewed documents prepared by DOE staff and national laboratories concerning the DOE technology base including the CO_2 research efforts. This latter assessment was conducted at the request of ERAB as part of the 1980 effort of the R&D Panel to assess R&D needs in the Department. Brief program descriptions and budget information were also provided by the staff for the program ranking exercises.

C. Why was the program given such a high priority?

Answer C:

The CO_2 question was generally thought to be a potential ultimate "show-stopper" in terms of expanded fossil fuel usage should the accumulation of CO_2 in the atmosphere prove to be a serious problem. It was also generally agreed that the scientific basis for assessing potential CO_2 problems is inadequate given the complexity and present state-of-the-art in atmospheric sciences. As explained in the report, climate and CO_2 research is needed to provide information for future public policy decisions and the Federal Government has the principal responsibility for support of long-term, basic environmental research of this kind.

In terms of the specific evaluation criteria used in the R&D Priorities study, climate and CO_2 research ranked high for its potential contributions to scientific knowledge, urgency with regard to the lead time needed to complete the research, DOE mission impact and Federal role. Out of a highest possible score of 3.00, climate and CO_2 research was ranked by each criterion as follows (see R&D Priorities Report for criteria definitions):

Scientific Potential	2.44
Inventive Potential	1.88
Mission Impact	2.69
Urgency	2.75
Federal Role	3.00

3. The Board Report indicated that funding for the program should be increased.

A. How much should it be increased? (FY 1982 $12 million FY 1983 request $8 million)

Answer A:

The Board deliberately did not specify a percentage change that would correspond to its recommendations for "more" or "less" funding, recognizing that specifying budget figures is the proper province of program managers and of the responsible Congressional Committees. Generally, the Board members are aware of the principle that in the support of R&D programs very abrupt changes in funding level can be wasteful and are generally inefficient. My own interpretation is that "more" would correspond to a 20 to 30 percent increase. The Board used the President's FY 1982 budget as a base line and did not contemplate major changes from those levels.

B. What R&D programs should the funds be used for?

Answer B:

The Board did not attempt to specify programmatic objectives in any detail. This is the legitimate function of DOE program officials and the Administration to define in consultation with the cognizant congressional committees. Indeed, the CO_2 program within Basic Energy Science is well managed and can provide detailed program plans for expanded CO_2 research.

2. The Report states that "an intensified research effort is needed now in order to ensure that better information will be available for future decision making."

A. What is meant by "intensified research effort?" What changes should be made in the CO_2 R&D program?

B. What additional research should be conducted that is not now underway?

Answer:

The Board's effort was focused on setting overall priorities between major line items of DOE research and development. As stated above, we did not attempt to define research objectives within specific programs and have not been asked by DOE to do so. The DOE program office and scientists currently working on these problems are better equipped to define the specific nature of an intensified effort. However, the CO_2 and climate issue clearly requires a long-term effort. Data will need to be gathered and evaluated that allows estimates of the extent of the problem to be made with confidence. The program is presently proceeding to fund research aimed at unraveling the CO_2 effect from natural changes in climate.

ANSWERS TO QUESTIONS ASKED OF JAMES E. HANSEN

1. A. What additional research is needed to definitely associate this warming with increased CO_2 levels?

A broad research effort is needed, as a result of the complexity of the climate system and the fact that expected CO_2 climate effects do not yet overwhelm climate variations due to other causes.

To definitely associate climate change with CO_2 in the near future, it will be necessary to have a knowledge of other climate forcing mechanisms, e.g., solar variations, stratospheric aerosols, and trace gases; thus appropriate observational data are essential. The technology for such measurements exists, but there needs to be a commitment for long range research and monitoring - over a period of 10 years or longer.

It is also necessary to improve climate modeling capability for key processes such as atmospheric clouds and ocean circulation. This implies the need for extensive observations, as well as research and model development. Existing and planned satellite measurements may provide the needed cloud data, if the measurements, are adequately archived, processed and analyzed. Good progress on understanding the ocean circulation will be made if monitoring of transient tracers in the ocean is continued; however, other extensive studies of ocean processes will be needed.

1. B. How has this research been received in the scientific community since its publication?

It has generally been well received. Confirmatory data on the global temperature trend and sea level trend has been obtained by other scientists. I expect some technical comments about our paper to be published in Science, however, these do not modify our basic conclusions.

2. A. What are the sources of these trace gases?

The chlorofluorocarbons are manufactured primarily for use in spray cans and in refrigeration. Sources of nitrous oxide and methane are less certain. A substantial research effort is needed to understand the geochemical cycles determining the abundance of these gases. It is likely that combustion of fossil fuels and agricultural practices, e.g., use of fertilizers, affects the abundances of nitrous oxide and methane.

2. B. How do they contribute to the greenhouse effect?

The trace gases absorb in the infrared 'window' region of the spectrum (5-15 μM wavelengths) and thus trap thermal radiation, in the same manner as CO_2.

2. C. Compared to CO_2, how big a problem are these trace gases? How large could the problem become?

We estimate that these trace gases caused a greenhouse effect 70 percent as great as that of CO_2 during the 1970's. However the uncertainty is large, because the measurements of these gases are not of sufficient accuracy.

It is conceivable that these traces could surpass CO_2 in their greenhouse effect. Some of the trace gases contribute to the greenhouse effect by means of unsaturated bands in the middle of the 5-15 μM window, such that their contribution is nearly linear with increasing amount; this contrasts with CO_2, which contributes mainly via a strong band on the edge of the window. Thus the relative contribution of the trace gases may increase in the next century.

The chlorofluorocarbons would now be contributing more than CO_2 to the annual growth of the greenhouse effect, if their production had not been curtailed in the 1970's. This illustrates the potential importance of the trace gases, as well as the feasibility of effective controls.

3. A. and 3. B. Is the air temperature related to increased levels of atmospheric CO_2? What additional research is needed to "prove" that increases in CO_2 cause an increase in mean sea level?

The greenhouse gases are expected to cause a warming and the warming is expected to cause melting of ice sheets and thermal expansion of ocean water, thus a rise of sea level. The empirical evidence for changes of both global temperature and sea level is consistent with these expectations.

Key research needed to assess the connection of CO_2 amount and global temperature is discussed under 1. A. above.

The most crucial needed research on sea level concerns the sensitivity of the ice sheets to change of global temperature (and sea level), especially the rate at which disintegration may occur. This requires monitoring of the mass balance of the ice sheets, as can be obtained with accurate topographical measurements from a satellite, and studies of ice sheet processes. It is desirable to have a better network for monitoring sea level; a precise altimeter on a satellite could contribute to this, as well as to studies of ocean circulation and heat storage.

Answers of G. Kukla to the questions of Dr. J. H. Scheuer and Mr. A. Gore, Jr.

QUESTION 1A: How were sea ice positions from the 1930's determined and how accurate are they?

ANSWER: There were numerous whaling ships in the Antarctic waters during the 1930's. Because whales are frequently found in the vicinity of the ice edge, the ship logs included reports on the ice positions. These observations were critically analyzed and charted by Hansen, an experienced sea captain and by Herdman and Mackintosh. We relied heavily on the work of Mackintosh and Herdman, both of whom participated in the scientific expeditions of the DISCOVERY vessels, sent out on Antarctic cruises by the Discovery Committee of the British Royal Geographic Society and the Royal Society. They state the following in their paper:

> "We have included in the charts only those observations in which not only the position of the ice-edge but also the date are known, for the mean latitude of the ice-edge may vary considerably even in the same month, and an undated record is of little value. Furthermore, the plottings are intended to represent the actual outer boundary of the pack-ice belt, and any records such as abstracts from logs in which it is merely stated that pack-ice is in sight are disregarded unless there is something to show that the ship was actually at or near the true ice-edge, and not some distance within an area, for example, of open drift ice."

By "open drift ice" the authors were referring to sea-ice plumes which occasionally extend from the main pack ice field into open ocean. These highly mobile plumes can be mistaken for the pack-ice edge by an inexperienced observer who does not have enough time to monitor the ice movement. In addition, particularly in the Weddell Sea, an extensive ice tongue frequently forms in late spring. Different ice positions can then be reported depending on the direction of the ship's approach.

Due to the extensive experience of the preceding authors and because of the consensus of a relatively large number of independent reports, we are confident that our conclusions have not been significantly affected by the above problems.

QUESTION 1B: What has been the reaction of the scientific community to the publication of this research?

ANSWER: We sent the draft version of the manuscript to several colleagues, familiar with high latitude climate for comments, and adjusted the final version according to their suggestions. Most of our internal reviewers as well as the reviewers selected by the journal Science, stressed the need for underlining the large year-to-year and decade-to-decade variability of the climate system which prevents an interpretation of the observed variations as a definite sign of the CO_2 increase. We tried to make this point as clear as possible in the article as well as in the testimony.

A favorable report on our findings was published by the Bulletin of the American Meteorological Society (Vol. 62, p. 1607-1608). Our findings were also discussed at length in the News and Views section of the British scientific journal Nature (vol. 295, pg. 645-646). In summary, the journal states that our recent sea ice observations as well as the model versus observed surface temperature comparisons of the GISS group are consistent with a consensus of modeller's expectations for a climatic signal from increasing "greenhouse" gases. According to the journal, "the statistical significance of the results is simply too small and the number of unverified modelling assumptions too large to allow one to proclaim detection." This statement is concurrent with our view of possible link between the observed changes and the CO_2 rise.

QUESTION 2A:	How closely do the research results correlate with theoretical predictions (from climate models)?
ANSWER:	Most climatic modellers assume that the area of sea ice and the snow cover will decrease in both hemispheres as a result of the snow/albedo feedback.

The closest comparison of our findings with model predictions can be made in the high latitudes of the N. hemisphere, where we found that the recent zonally averaged surface air temperatures in spring and summer are higher than they were 40 years ago. We also found that the positive anomaly is approximately 4 times larger at latitude 80°N than at 65°N. The model of Ramanathan, Lian and Cess also predicts a considerablfy stronger warming at the latitude 85° than at 65°N. According to the model results, the 100% increase of CO_2 should raise the temperatures at 85°N in June by about 12°C, and somewhat less at 80°N. The CO_2 concentrations increased by 10-15% from the 1930's, so that the observed temperature difference of about 0.9°C along 80°N between the 1934-38 and 1974-78 pentads is in approximate agreement with the model's prediction. The one month difference in the timing of the peak response expected by Ramanathan et al., and the positive anomaly maximum found by us also agrees, because, as the CO_2 increases, the melt should occur earlier in the season.

In another numerical climate model, Wetherald and Manabe in 1981 predicted the largest temperature increase resulting from a quadrupling of CO_2 to occur in central Arctic in mid-winter. This should happen as a result of the arctic atmosphere being heated during the polar night by the warm ocean covered with only a thin layer of ice. Thick ice will not have time to develop, because all the ice in Arctic will melt in summer. Wetherals's and Manabe's results do not contradict those of Ramanathan et al., whose data are based on a doubling of CO_2 concentrations, a change insufficient to lead to a complete melt of the arctic ice in summer.

Today the sea ice is relatively thick in the Central Arctic throughout the year, so that the process predicted by Wetherald and Manabe can not yet be taking place.

QUESTION 2B: What additional research must be done to prove the correlation?

ANSWER: To prove the causative relation between the observed changes and the CO_2 we must eliminate any other possible causes including natural variability, solar activity, man made pollution etc. This objective, as we believe, can best be achieved on regional rather than global scales. Increased attention should be paid to the transitional seasons of the year and to the snow and ice marginal belt.

QUESTIONS 3A,B: How long will it be before we can say definitely that CO_2 is causing climate changes? When will the proof of the CO_2 impact become available?

ANSWER: We are interested in learning if and when the CO_2 will dominate the climate change. We will be able to answer this question as soon as the climatic impact of variables other than CO_2 is reliably understood. Because some variables such as volcanic ejecta fluctuate at random, the prediction of the CO_2 climate impact will always include elements of uncertainty. However, a reasonably accurate probability forecast in my opinion can be obtained in less than 5 years.

Kane Questions

1.a. Mr. Scheuer: On page 3 you state, "I believe that this amount is a satisfactory compromise between the clear need at this time to reduce Federal expenditures and the unquestioned importance of the CO_2 problem." What direction and scope of the CO_2 program was reduced or altered as the result of this compromise?

Dr. Kane: The direction and scope of the program have been brought to focus on establishing the scientific data base necessary for decision. The majority of the reductions have been achieved naturally rather than by stopping work. For example, the Transient Tracers in the Ocean was requiring $2,000,000 a year to take measurements. Now we are analyzing the data and the costs are at $500,000 a year.

1.b. Mr. Scheuer: What are the future plans for both the level of funding and the program direction for the CO_2 program?

Dr. Kane: The program will continue to be a focused program and funded at the 1983 level. Larger budgets will be requested as the need arises. Specific plans will be delivered with any such enhanced budget requests..

1.c. Mr. Scheuer: How will this reduction in CO_2 research funding alter the long-range plans and time schedules for the program?

Dr. Kane: We will deliver an interim report in mid 1985 as promised. The long range plans also remain unchanged.

Kane Questions

2.a. Mr. Scheuer: On page 3 you state "We plan to use the larger FY 1982 funding to bring some of the less central research to a timely and cost effective conclusion, and to concentrate our FY 1982 effort on the most essential components." What do you define as "less central research? The FY 1983 budget request lists a reduction in carbon cycle research.

Dr. Kane: In a period of research budget belt-tightening, it seems prudent to focus on critical scientific questions of what happens to fossil CO_2 when introduced into the atmosphere. It is important to determine how rapidly the excess CO_2 is absorbed by oceans and the terrestrial environment. A credible assessment of the CO_2 issue first requires a clear understanding of global CO_2 dynamics and the first order climate response to CO_2. Understanding the earth's geophysical response to CO_2 is a central requirement. It provides the basis for other assessments of effects.

Less urgent are studies of secondary and tertiary impacts. Analysis of societal or environmental impact requires believable scenarios of climate change. It just isn't possible at the present time to formulate credible climate situations which can be attributed to CO_2 change until we have a better understanding of the global climate system, what causes natural climate variability, and the role of CO_2, among other things, in climate perturbation.

The FY 1983 reductions in carbon cycle research were anticipated as projects were completed as a part of a directed program.

2.b. Mr. Scheuer: What are the programs that will be concluded at the end of FY 1982?

Dr. Kane: The Transient Tracer Ocean experiments are coming to an orderly conclusion, as well as research on economics in the agricultural field, and instrumentation development.

Kane Questions

3.a. Mr. Scheuer: Last year saw the CO_2 program moved from the Office of Environmental Research to the Office of Basic Energy Sciences, a 1981 mid-year budget reduction of $2 million, $14 to $12 million, and finally on FY 1983 budget request 30% below FY 1982 appropriations, $12 to $8 million. What are the future plans for the CO_2 research program with respect to funding, direction, level of effort, etc.?

Dr. Kane: As I stated earlier, the focused direction will be maintained. The future funding level and level of effort will be the object of specific plans.

3.b. Mr. Scheuer: Are there any plans now to alter the programs from the FY 1983 budget requests?

Dr. Kane: No, there are no such plans at the moment.

Kane/Koomanoff Questions

1.a. 1.b. Mr. Scheuer: In the FY 1983 budget request to Congress the statement is made that, "...research on the global carbon cycle will be reduced..." Specifically, what research will be cut? What is the reason for cutting one of the most important aspects of the program, carbon cycle R&D, and not some other research?

Dr. Kane: Several projects have come to completion. For example, in 1981 the Transient Tracers in Oceans was funded at $2 million a year for data collection. Now data analysis has started and funding is at $500,000 per year. A feasibility study to use satellites to access the biospheric carbon reservoir will be completed this year. We have also decreased our replication by funding fewer projects in a given area such as instrumentation development. Some of the programs are still under examination so I cannot give you specifics on every one.

Our proposal refusal rate will increase in the carbon cycle. It will begin to fit more closely my rule of thumb that I mentioned earlier.

Further, we are working with our sister agencies, NSF, NOAA, and NBS, so that DOE and NSF provide for research measurements and standards, and NOAA and NBS provide for routine monitoring and standards.

2.a. Mr. Scheuer: In the FY 1983 budget the justification for program cuts given is "The growth rate of fossil fuel emissions has slowed...A lower rate of growth in CO_2 emissions provides more time to evaluate possible climate effects, environmental consequences and energy policy implications." Do you have any data that shows atmospheric CO_2 levels are decreasing?

Dr. Kane: There are no data which show decreasing atmospheric CO_2 levels. This would not be expected as long as CO_2 emissions continue at present levels. The latest measurements show that atmospheric CO_2 continues to increase by about 1.5 ppm per year. This increase appears to be related to continued emissions from fossil fuel and possibly other sources.

2.b. Mr. Scheuer: Do you have any data that the rate of increase in atmospheric CO_2 levels, 315 to 328 ppm in the past 22 years, is also decreasing?

Dr. Kane: The change in rate of growth of fossil CO_2 emissions would not immediately be reflected in the atmosphere as long as the quantity of CO_2 release remains essentially constant, about 5.2×10^9 tons.

2.c. Mr. Scheuer: On the other hand if the growth of "fossil fuel emissions" increases will the CO_2 R&D program also be increased?

Dr. Kane: This is dependent upon the type of research. Some areas of CO_2 research can be accelerated and provide quicker answers, and in these areas the R&D effort would be increased.

Other areas of CO_2 research cannot be accelerated no matter what the funding level due to the nature of the research. These areas require certain amounts of time, such as the TTO experiment, which money cannot buy.

Koomanoff Questions

1.a. Mr. Scheuer: On page 2 you list the issues that are unknown/uncertain. Two are: The level of CO_2 that is acceptable in terms of minimum impact.
The costs and benefits of higher CO_2 concentrations.
What research is DOE conducting that will help clarify these issues?

Mr. Koomanoff: DOE is conducting research on the carbon cycle. Until we have a much better grasp of the true CO_2 sources, CO_2 removal mechanisms and the times involved, these issues will remain uncertain. Costs and benefits of higher CO_2 concentrations can't really be determined without knowing more about the carbon cycle.

1.b. Mr. Scheuer: The "costs and benefits" of higher CO_2 concentrations is a type of risk analysis. Are you decreasing R&D on the risk analysis aspects?

Mr. Koomanoff: The data base is insufficient to permit a meaningful effort on risk analysis. We are continuing R&D to develop the data base and learn how to use it for such work in the future.

1.c. Mr. Scheuer: What are the future plans for risk studies?

Mr. Koomanoff: In 1985 our report will include any work that can be done, but will most likely define what we expect to deliver at a later date. By 1988-1990 the improved climate models, vegetation effects and carbon cycle models will allow us to conduct meaningful risk analyses.

Koomanoff Questions

2.a. Mr. Scheuer: On page 2 you state, "We must improve our understanding of the fundamental relationships between CO_2 concentration and climate, increase data collection, improve measurements, and develop reliable models. We can then answer specific questions about the sources and sinks of carbon dioxide." If we need to improve fundamental knowledge why is the budget request of FY 1983 for carbon cycle research reduced?

Mr. Koomanoff: Carbon cycle research required some heavy up-front costs that are not ongoing. This accounts for most of the reduced budget request for this category in FY 1983. For example, nearly one-million dollars of ship costs for North Atlantic Oceanographic research will not recur in FY 1983 while scientists focus on interpretation and modeling of data collected in FY 1983. Also, measurement of atmospheric CO_2 is scheduled for phase-down as the National Oceanic and Atmospheric Administration assumes responsibility for this research. A few projects on biosphere CO_2 source and ocean chemistry of CO_2 will be concluded because they have achieved objectives by FY 1983.

2.b. Mr. Scheuer: Does your statement mean that the sources and sinks of CO_2 will not be studied until after the fundamental relationships are understood?

Mr. Koomanoff: No. Knowledge of fundamental relationships provides the basis for answering questions about sources and sinks of carbon dioxide and will define better research opportunities. A key objective of the program is to identify and quantify CO_2 sources in addition to fossil fuel emissions. Carbon dioxide from a disturbed biosphere is one alleged source which must be understood before one can place confidence in models of the global carbon cycle. Another key objective is to quantify the ocean's capacity for removing fossil CO_2 from the atmosphere. Research on removal of CO_2 by means of ocean chemistry and circulation is the basis for understanding an important CO_2 sink of the global biogeochemical cycle.

2.c. Mr. Scheuer: What is the FY 1983 level of funding for R&D into the sources and sinks of CO_2?

Mr. Koomanoff: Approximately $1.6 million is scheduled for continuing research on biospheric sources and ocean sinks in FY 1983.

3.a. Mr. Scheuer: On page 4 you state, "It may never by possible to attribute a climate change directly to an increase in atmospheric CO_2." There are several research efforts, including today's witnesses for example, that are close to doing just what you say may never be possible. On what do you base your statement?

Mr. Koomanoff: We are looking for a CO_2 signal that can be unequivocally attributed to increases in atmospheric CO_2. I believe the witnesses, particularly Dr. Kukla, have carefully reported to you the limits of their data. The results are not inconsistent with increased CO_2 but are far from a fingerprint. Let me give you an example. Dr. Hansen's recent paper in *Science* shows a curve fit for the temperature record with the equivalent of a 2.8°C equilibrium temperature rise for doubling of CO_2. He states that a model with a 1.4°C equilibrium rise for doubling CO_2 also fit the curve. Other researchers find similar ranges. Several even find no evidence of a CO_2 induced rise. This is mainly the fact that a CO_2 rise would be affecting only the last few years of the record. It's like trying to fit a curve through one point. There are lots of options. Our models and data are also incomplete. We do not know exactly how to calibrate in the sun's changes, volcanoes, ocean time lags, and other important factors.

3.b. Mr. Scheuer: What research efforts does DOE have underway, that could provide the direct link between climate change and CO_2 increase?

Mr. Koomanoff: We are examining the complex relationships between the current critical variables such as temperature and water vapor on various time and spatial scales. The models direct us to the variables, space scales and time scales of interest, in other words the signal. The climatic data base can then be compared to the signal and examined for evidence of changes specifically related to CO_2.

3.c. Mr. Scheuer: What are the future plans to study these links?

Mr. Koomanoff: We will continue analyses using key data sets comparing the model generated signals to the real data and explain our activities as new concepts are developed.

Koomanoff Questions

4.a. Mr. Scheuer: On page 4 you state, "Increased atmospheric CO_2 may benefit vegetation and crops because it is an essential ingredient for plant growth. What studies are underway on the beneficial aspects of increased atmospheric levels of CO_2?

Mr. Koomanoff: Several investigations of the fertilization effect have been initiated. Chiefly, a joint program with the U.S. Department of Agriculture, Agriculture Research Service is assembling data and developing models to assess soybean growth response to elevated atmospheric CO_2. Future budgets permitting, other crop responses will be determined and the experimental data and models will aid national assessments of CO_2 enhancement of agricultural productivity. On an exploratory scale, are other studies of relative responses of native species to elevated CO_2. Some research is devoted to enhancement of photosynthesis of trees to determine if increased carbon storage may occur in a future higher CO_2 world.

As a point of information, this May 23-28, we are jointly sponsoring with the Department of Agriculture and the American Association for the Advancement of Science a conference on rising atmospheric carbon dioxide and plant productivity in Athens, Georgia.

4.b. Mr. Scheuer: Does any evidence indicate that increased levels of CO_2 will not help or might even harm plant growth?

Mr. Koomanoff: The majority of observations of plant response to CO_2 suggest increased growth - a positive response. However, a group of plants possessing the C_4 pathway of carbon metabolism exhibit very limited growth response, and at about 1000 ppm of CO_2, nearly 3 times the ambient, a slight reduction of growth of maize, a representative of this group, may occur. But observations of this response are very limited, and it is not known if the observed growth response would occur under field conditions. Preliminary laboratory observations suggest starch accumulation in leaves and accelerated senescence at high exposure to CO_2, greater than 1000 ppm. Because CO_2 participates in may plant biochemical reactions, the possibility of potentially detrimental effects cannot be disregarded especially at high levels of CO_2 exposure. Actual observation of harmful effects on plant growth are exceedingly rare.

APPENDIX II

ADDITIONAL STATEMENT FOR THE RECORD

TESTIMONY SUBMITTED BY
FRIENDS OF THE EARTH
TO
THE SUBCOMMITTEE ON NATURAL RESOURCES,
AGRICULTURAL RESEARCH & ENVIRONMENT
AND
THE SUBCOMMITTEE ON INVESTIGATIONS AND OVERSIGHT
OF
THE COMMITTEE ON SCIENCE & TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES
MARCH 25, 1982

MR. CHAIRMAN, FRIENDS OF THE EARTH COMMENDS YOU FOR HOLDING THIS IMPORTANT HEARING ON CO2 AND CLIMATE CHANGE. FRIENDS OF THE EARTH IS AN INTERNATIONAL ENVIRONMENTAL ORGANIZATION WITH 28,000 MEMBERS IN THE UNITED STATES AND AFFILITATES IN 27 NATIONS THROUGHOUT THE WORLD.

THIS HEARING COMES AT A CRITICAL TIME WHEN EVIDENCE IS ACCUMULATING THAT CLIMATE CHANGE COULD BE ONE OF THE MOST SERIOUS AND IRREVERSIBLE EFFECTS OF ACCELERATING FOSSIL ENERGY USE. AT THIS VERY MOMENT, HOWEVER THE REAGAN ADMINISTRATION PROPOSES TO DRASTICALLY CUT FEDERAL EFFORTS TO UNDERSTAND THIS PROBLEM IN FY 1983. FRIENDS OF THE EARTH STRONGLY URGES THE CONGRESS TO REJECT THE REAGAN PROPOSALS.

WHILE THE PRECISE CLIMATE EFFECTS OF A GLOBAL WARMING ARE NOT FULLY KNOWN WE MUST DO OUR BEST TO FIND THE ANSWERS BEFORE MAKING FURTHER NEW COMMITMENTS TO USE FOSSIL ENERGY, PARTICULARLY COAL. THE UNITED STATES HAS A SINGULAR RESPONSIBILITY IN THIS REGARD BECAUSE WE POSSESS THE SECOND LARGEST COAL RESERVES IN THE WORLD, AFTER THE

SOVIET UNION, AND BECAUSE WE ARE THE LARGEST SINGLE CONSUMER OF FOSSIL ENERGY.

CO2 IS NOT THE ONLY TRACE GAS WITH THE POTENTIAL TO CAUSE CLIMATE CHANGE. IT IS NOW ESTIMATED THE OTHER INDUSTRIAL AND AGRICULTURAL BY-PRODUCTS SUCH AS THE FREONS, AND NITROUS OXIDE MAY INCREASE THE "GREENHOUSE EFFECT" BY 70%. THUS CLIMATE CHANGE WILL POTENTIALLY AFFECT INDUSTRIAL AS WELL AS ENERGY POLICY.

MR. CHAIRMEN, FRIENDS OF THE EARTH HAS RECENTLY PUBLISHED A PAPER DETAILING THE CURRENT SCIENTIFIC UNDERSTANDING AND PROGRAMMATIC STATUS OF CO2 AND CLIMATE CHANGE. A COPY OF THIS PAPER BY ANTHONY SCOVILLE IS ATTACHED TO THIS TESTIMONY AND WE REQUEST THAT IT BE MADE PART OF THE RECORD OF THIS HEARING.

AS THE ARTICLE MAKES CLEAR, THE REAGAN ADMINISTRATION PLANS TO REDUCE FUNDING FOR DOE'S CO2 PROGRAM BY ONE-THIRD FROM $12 MILLION TO $8 MILLION FOR FY 1983. AT OTHER AGENCIES FUNDING IS LEVEL WHICH MEANS AN EFFECTIVE REDUCTION OF RESEARCH AFTER INFLATION IS CONSIDERED. WE NEED TO GET THE ANSWERS JUST AS SOON AS POSSIBLE WHILE THERE IS STILL TIME TO ACT IF POTENTIAL CLIMATE CHANGE TURNS OUT TO BE AS SERIOUS AS PREDICTED.

IN CONDUCTING INTERVIEWS FOR THIS ARTICLE ADMINISTRATION SPOKESMEN EXPRESSED SKEPTICISM ABOUT THE SERIOUSNESS OF CLIMATE CHANGE; CURRENT DOE RESEARCH PLANS NO INPUT TO ENERGY POLICY FOR THE NEXT

DECADE AT LEAST. AT THE SAME TIME, HOWEVER, THE DIRECTOR OF DOE'S PROGRAM, DR. FREDERICK KOOMANOFF, IS SIMPLY UNINFORMED ABOUT THE STRENGTHS AND LIMITS OF CURRENT CLIMATE MODELS. SO FAR AS WE CAN DETERMINE IT APPEARS THAT THE ADMINISTRATION SEEKS TO CONFIRM ITS SCIENTIFIC NAIVETE BY REDUCING THE RESEARCH WHICH MIGHT DISPROVE ITS PRECONCEPTIONS.

LAST YEAR DOE'S ENERGY RESEARCH ADVISORY BOARD RECOMMENDED INCREASING FUNDS FOR CO2 RESEARCH ABOVE THE $16 MILLION THEN REQUESTED FOR FY 82 BY PRESIDENT REAGAN FOR DOE ALONE. WE STRONGLY SUPPORT THAT RECOMMENDATION. FRIENDS OF THE EARTH SPECIFICALLY URGES THAT INCREASED EFFORT BE DEVOTED TO THE EFFECTS OF NON-CO2 TRACE GASES SUCH AS THE "FREONS". WE URGE RESTORATION OF FUNDING FOR COMPUTER MODELING WITH SPECIFIC ATTENTION TO SIMULATING SMALL TEMPERATURE INCREASES WITHIN HIGH CLIMATIC "NOISE". LAST AND MOST IMPORTANT, FRIENDS OF THE EARTH BELIEVES THAT FAR GREATER EFFORT MUST BE DEVOTED TO THE SOCIAL, ECONOMIC AND AGRICULTURAL CONSEQUENCES OF GLOBAL WARMING. FUNDING HAS BEEN ALMOST ELIMINATED IN THIS AREA AT DOE.

NOT ONLY ARE SOCIAL AND ECONOMIC VARIABLES FAR MORE UNCERTAIN THAN THE CLIMATE SCIENCE BUT BETTER UNDERSTANDING OF SOCIAL AND ECONOMIC IMPACTS CAN HELP PLAN CLIMATE RESEARCH EFFICIENTLY IN ORDER TO SUPPLY RELEVANT INFORMATION AS OUR UNDERSTANDING OF GLOBAL WARMING INCREASES. DR. ROGER REVELLE AND DR. LESTER LAVE BOTH MADE THIS POINT TO THIS COMMITTEE LAST SUMMER.

MR. CHAIRMEN, FRIENDS OF THE EARTH COMMENDS YOUR SUBCOMMITTEES FOR THEIR CONCERN ABOUT CO2 AND CLIMATE CHANGE. GLOBAL WARMING COULD BE ONE OF THE MOST SERIOUS AND IRREVERSIBLE ENVIRONMENTAL PROBLEMS YET FACED BY MAN. MOST IMPORTANT, WHILE THE WARNING SIGNS DO LOOK INCREASINGLY OMINOUS, WE DO NOT KNOW ALL THE ANSWERS YET.

FRIENDS OF THE EARTH BELIEVES THAT CLIMATE CHANGE MUST NOW BE INCLUDED AS PART OF ENERGY AND ECONOMIC INNOVATION POLICY. FACED WITH THE POSSIBLE THREAT OF GLOBAL WARMING IT IS IRRESPONSIBLE TO DECIMATE PROGRAMS FOR ENERGY CONSERVATION AND SOLAR ENERGY AS THE REAGAN ADMINISTRATION IS DOING.

THANK YOU.

by Anthony Ellsworth Scoville

Why the US Ignores The Greenhouse Effect

Atmospheric CO_2 is headed toward dangerous levels. Why doesn't the Administration want to know about it? Because it would have to change its attitude on energy development—now.

EARLY LAST YEAR, Secretary of Energy James Edwards sat down with his program managers and asked them three questions: How does your program help national security, how does it increase energy production, and can private industry perform the job? The programs in question would live or die by the answers provided.

Since 1975 David Slade had directed the Department of Energy (DOE) study of global climatic change. He had little doubt of the program's validity. Indeed, everyone from representatives of the National Science Foundation to President Reagan's science advisor had identified atmospheric build-up of carbon dioxide (CO_2) as worthy of attention in energy policy. A NASA scientist had warned that global warming from CO_2 build-up would be detectable in the 1980s, and later that year, two Columbia University researchers would find that the Antarctic ice sheet had shrunk by almost a million square miles between 1973 and 1980—findings, they would say, that fit their theories of the increase of the greenhouse effect "just where we expected."

Slade fought long and hard, but it was all but impossible for him to demonstrate to the former dentist from South Carolina that a program that monitored the effects of fossil-fuel burning could in any way increase energy production.

The result was ugly, if predictable. Slade was transferred to DOE's small acid-rain research department. The Administration then attempted to slash the CO_2 budget from $16.7 million to $8 million for 1982. Fortunately, Congress opposed the cuts and salvaged the program, which exists today in a severely neutered form, one that an economist from the Brookings Institution termed "disastrous."

Douglas Pewitt, then acting director of DOE's Office of Energy Research, told the Natural Resources Defense Council that Slade was reassigned because "his management did not reflect the best scientific management." When we interviewed Pewitt, however, he vehemently denied the statement, saying he had been quoted out of context. And as other voices from within the administration addressed the charges of mismanagement, it became clear that the issue was not so much one of management ability as it was one of research philosophy: the administration felt that Slade was more concerned with researching the potential social and economic impacts of climatic change than with understanding the physical nature of climate itself.

Such a division is nothing new; there is a long history of disagreement between those scientists who insist on pure geophysical study first and those who hold that analyzing impacts while developing data can not only guide research but can also suggest prudent policies that might be desirable even in the absence of perfect knowledge. A group of the former is predominant in the Reagan administration. As Joel Snow, Senior Science Associate of the Office of Energy Research at DOE, put it, "At a time when geophysical information is insecure. . .the government should not fund idle speculation."

But research into the socioeconomic impact of climatic change from fossil fuel burning is much more than "idle speculation," and it is for this reason that the Reagan administration has moved to cut it out of not only the Department of Energy but the National Science Foundation as well, where it cut funds for the social and economic sciences from $31.4 million in 1980 to $17.6 million in 1982. The Administration considers such research an unwarranted intrusion on individual and corporate decision making. It tolerates CO_2 research only to satisfy congressional pressure and only to the point that it does not question economic and energy policy in the near future.

And so, Edwards's criteria focus full attention on energy production, none on its consequences. And even though Dr. George Keyworth, President Reagan's science advisor, can tell the House Science Committee that climatic change "is an important issue, one that should be taken into account in formulating an overall approach to energy policy," the administration's attitude remains one of studious procrastination.

There is of course no way that researching CO_2 build-up cannot call into question the current administration's energy policy. We know this from evidence of predicted increases of the greenhouse effect, increases first predicted by scientists 80 years ago. As we shall see, the administration is cutting funding into CO_2 research so that it can justify its deliberate ignorance of the issues at hand. It is as if it were saying, if we do not look for evidence, then evidence does not exist. Nothing could be further from the truth.

BRIEFLY, the greenhouse effect is this: When coal, oil, and natural gas are burned, the two principal combustion products are water vapor and carbon dioxide, about half of which remain in the atmosphere. Both are transparent, so sunlight readily passes through them. The earth in turn radiates infrared radiation, which the atmospheric gases trap, thus raising the earth's temperature. Without this trapping effect, the earth would be like Mars, cold and incapable of supporting life.

A little CO_2 goes a long way, however, and the gas is increasing in the atmosphere. This build-up closely parallels the worldwide use of fossil fuels over the last century. Before the Industrial Revolution, the atmospheric CO_2 level was about 280 parts per million (ppm). Today, that level is about 338 ppm. Tests in Hawaii and the South Pole show that almost one-third of that increase—from 315 ppm to 338 ppm—has occurred over the last two decades.

What do these changes mean? In January, Dr. James Hansen of NASA's Goddard Institute for Space Studies reported that global warming should be detectable in the 1980s, and that large climatic changes will occur in the next century even if coal burning is phased out beginning in

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Anthony Ellsworth Scoville was a science consultant to the House Science Committee's Subcommittee on Science Research and Technology. He is writing a book on global climatic change and economic development, to be published next year by Friends of the Earth. Research for this story was made possible, in part, by a grant from the Tortuga Foundation.

the year 2000. Hansen also warned that fossil energy is not the only cause of such change. Other such trace gases as methane, nitrous oxide (from chemical fertilizers), and freons (used as refrigerants) could amplify the greenhouse effect by 70 percent.

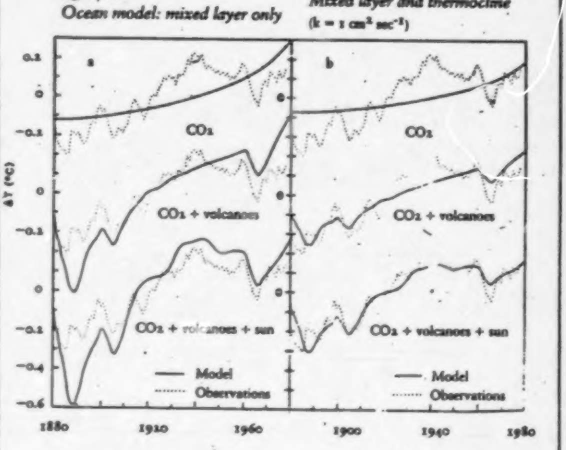
Hansen has developed a computer model that can simulate climate changes to such a fine degree that after combining the predicted effects of atmospheric CO_2 with the shielding of volcanic dust, he is able to account for 75 percent of the variation in the average world temperature over the last century. He has found that the average has risen 0.4 degrees since the 1880s.

Hansen's work receives independent confirmation in a forthcoming article by Ronald Gilliland of the High Altitude Observatory in Boulder, Colorado. Gilliland concludes that global warming may have been inhibited since 1940 by a downswing in a 76-year solar cycle—and that around the year 2010 an upswing in that cycle could seriously amplify global warming caused by fossil-fuel burning.

If fossil fuel consumption grows by 4 percent a year, as it did prior to 1973, atmospheric CO_2 could double by 2025—a date within the lifetimes of electric power plants being planned and built today. If consumption grows by 2 percent a year, as it has since 1973, mainly in response to higher prices, then CO_2 levels wouldn't double until the latter half of the 21st century. And a soft energy path such as that proposed by Amory Lovins, Wildrid Bach, and Florentin Krause would reduce fossil energy use to a fraction of today's level over the next 50 years. Thus, CO_2 levels could be greatly reduced—but only if we act now.

In any case, prevailing scientific opinion estimates that if atmospheric CO_2 doubles, the average world temperature will increase 1.5 to 4.5 degrees centigrade (2.7 to 8.1 degrees Fahrenheit). Hansen believes that this consensus neglects such factors as greater feedback between the oceans, air, ice, and clouds, and the contributions of the other greenhouse gases—nitrous oxide, freons, and the like—and that temperatures would tend well toward the upper edge of that range. The consensus is that the higher

Figure II



Ocean model: mixed layer only

Mixed layer and thermocline

temperatures would last 1000 years or more.

What would be the consequences to mankind should world temperature increase? The Antarctic ice melt mentioned earlier has attracted much attention, but the flooding of coasts and cities which would occur if the ice melted completely would take several centuries. Of more immediate concern is that Arctic sea ice, which is only seven to 18 feet thick, could melt in a matter of decades, especially if Siberian fresh water is diverted for agriculture, as the Soviet Union now contemplates doing.

Hermann Flohn, founder of the Institute of Meteorology at the University of Bonn, warns that an ice-free Arctic Ocean would "most probably lead, after a series of climatic weather extremes, to a displacement of the earth's climatic zones by 400 to 800 kilometers [250 to 500 miles northward]. This would necessarily affect mankind as a whole, beneficially in some areas but destructively in many others, drastically changing freshwater supply and agricultural productivity."

Dr. William Kellogg of the National Center for Atmospheric Research has written that if warmer prehistoric climates are any indication of the influence of CO_2-induced temperature changes, US and Soviet grain belts may suffer significant droughts. He told us that the Arctic ice cap could melt during the summer if the average polar temperature rises by only five degrees centigrade. Polar temperatures are expected to rise at three to five times the average world rate. Thus, substantial climate change could occur if world temperature increases by only a degree and a half. This may well happen if atmospheric CO_2 reaches about 420 ppm, just slightly greater than the level that will be reached if gas and oil reserves—which comprise only 15 percent of the world's recoverable fuels—are exhausted. Should this level be reached, said Kellogg, "The earth will have an average surface temperature which hasn't existed for three million years."

Flohn writes that "the European revolutions of 1789 and 1848 occurred after a succession of years with bad weather, bad harvests, and high cereal prices. . .what has happened can happen again." Flohn firmly believes that "this risk is unacceptable and must be avoided even at very high cost."

CLIMATIC CHANGE will not be simply a field experiment in atmospheric science but a test of man's ability to adapt to unprecedented environmental conditions. However, it isn't as if such change is beyond our control—if we act soon. As the Council on Environmental Quality concluded in its January 1981 report: "Preserving the option of holding atmospheric CO_2 below 1.5 or 2.0 times the preindustrial level means that planning for action on an unprecedented global scale would have to begin now. . . .The conclusion is inescapable that the CO_2 problem should not be isolated from current debate on long-term energy strategy."

However, even though its scientific spokesmen are uninformed, the Reagan Administration continues to perpetrate a worldwide experiment that is close to altering world climate even now. It refuses to acknowledge that the rate of energy consumption and the types of energy used are political and economic choices, controlled variables, not uncontrolled variables of atmospheric science.

It may be that the administration's attitude reflects its own ignorance. For example, Frederick Koomanoff, who replaced David Slade, told us repeatedly that computer-based climate models were of little practical value because they could not predict how climate would respond in situations that involved less than a doubling of atmospheric CO_2. That statement is simply not true.

Both Hansen and Syukuro Manabe of the Geophysical Fluid Dynamics Laboratory at Princeton—two of the world's most respected climate modelers—told us that their models are quite capable of portraying small temperature increases but that to obtain reliable predictions at low levels requires many hours of computer time. The Reagan Administration, however, proposes to cut 1983 funds for computer modeling by 40 percent (from $3.3 million to $2 million). In short, the administration will support its ignorance by simply refusing to fund the processes that could prove it wrong.

It is therefore quite understandable that

Koomanoff would tell us that he doesn't see CO_2 research affecting energy policy until the 1990s at the earliest. The administration's attitude was pretty well summed up when Douglas Pewitt, now an assistant presidential science advisor, testified before the House Science Committee that "I think it's very important to understand [CO_2] build-up. . . .[but] I don't share your sense of urgency." It is very hard to share a sense of urgency when you lack a fundamental grasp of the cutting edge of climate science and refuse to fund the research that could help you develop that understanding.

In addition, Koomanoff has virtually eliminated funding for socioeconomic research, leaving the program in a state that Lester Lave, an economist at the Brookings Institution, has called "disastrous." Lave points out that "leaving the physical scientists to themselves is not going to give us the answers." As he told the House Science Committee last summer, "You have to know not just generically that human beings burn fossil fuel and cause atmospheric CO_2 to increase; you have to know how much and when."

For the record, Koomanoff has provided funds for a small task force on "mitigation and control," which skeptics believe implies such "technofix" cures as scrubbing CO_2 from generator smokestacks and pumping it into the deep sea. A 1980 DOE study concluded that such a scheme would use over 50 percent of the energy generated.

ROGER REVELL, chairman of the *Energy and Climate* study prepared by the National Academy of Science, told the House Science Committee that "in adding CO_2 to the atmosphere mankind is unintentionally conducting a great experiment. This experiment can be expected to increase scientific understanding of ecological systems. . . .But, from the standpoint of governments and peoples, the major problem to be solved is to understand the nature of the impacts on societies, with the objective of avoiding or ameliorating unfavorable impacts and gaining the most benefit from favorable impacts."

The United States and the other developed nations bear the principal responsibility for undertaking this experiment. When global warming becomes significant, say William Kellogg and Robert Schware in *Climate Change and Society*, these nations will have contributed over 70 percent of the increased CO_2 in the atmosphere. Temperatures will not return to current levels for over a thousand years—no matter how much fossil fuel consumption is then reduced by either the developed or developing countries.

In recognition of this, the DOE's Energy Research Advisory Board gave "high priority" to CO_2 research and recommended an increase in the $16.7 million requested by President Reagan in March 1981. Actual expenditures for 1982, however, will be about $12 million, and only $8 million has been requested for 1983. (See box.) The Reagan administration continues to refuse to acknowledge that it can at least study, if not control, the most important variables in this very risky experiment. And Secretary Edwards, the dentist from South Carolina, just continues to drill and scrape, searching for ever more and ever cheaper oil and coal.

*What You Can Do: Write your Senators and Representatives. Also, write these Representatives: James H. Scheuer (D-N.Y.), Chairman, Subcommittee on Natural Resources, Agricultural Research, and Environment, and Albert Gore Jr. (D-Tenn.), Chairman, Subcommittee on Investigation and Oversight, (House of Representatives, Washington, DC 20515).

Contact FOE for names of other concerned Representatives and Senators. They need your support. Let us know if any seem particularly receptive so that we can follow up.

Where the Ax Has Fallen

EVEN AS REAGAN SPOKESMEN profess their desire to clear up the scientific uncertainties of CO_2 and decry a "scare psychosis" fomented by "environmentalists," they are decreasing their funding of CO_2 research. At DOE, the lead CO_2 agency, Reagan has requested a 33 percent cut for 1983 while support at other agencies has remained constant. At a minimum, given a 10 percent rate of inflation, CO_2 research will suffer a 26 percent reduction. So much research time will be devoted to a scramble for funding that overhead will be increased and real research reduced by up to 30 percent.

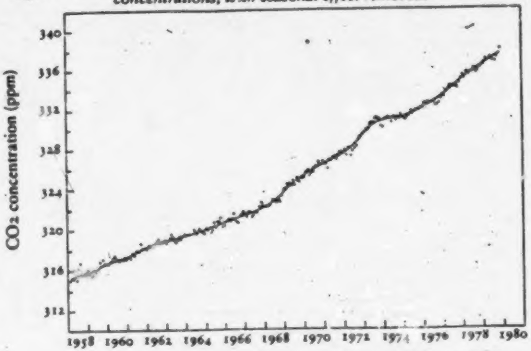
The figures speak for themselves:

	FY 1982	FY 1983
Department of Energy (DOE)	$12 million	$8 million
National Aeronautics & Space Administration (NASA)	$100,000	-0-
National Science Foundation (NSF)	$5.4 million	$5.4 million ± 1.0*
National Academy of Sciences (NAS)	$175,000**	$175,000**
Environmental Protection Agency (EPA)	$250,000 $560,000	$500,000 $560,000
US Geological Survey (USGS)	$560,000	$560,000
Department of Agriculture (DOA)	$900,000	$900,000
National Oceanic & Atmospheric Administration (NOAA)	$2.5 million	$2.5 million
TOTAL	$21,885,000	$17,860,000

* NSF funding may vary by $1 million depending on the quality of CO_2 proposals submitted. Other agencies' budgets may vary somewhat depending on the extent to which multipurpose research is included as part of CO_2 research.

**Not part of total; the Academy's work is included in the DOE and NSF figures.

Figure I *Mauna Loa monthly averages of atmospheric CO_2 concentrations, with seasonal effect removed.*



SOURCE: C.D. Keeling and Co-workers, Scripps Institution of Oceanography.

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